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Disaggregated analysis of ecosystem services in southwestern Ethiopia

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Abstract

Ecosystem services (ES) are the benefits that humans obtain from their interactions with ecological structures and functions. The ES concept is closely linked with sustainability, however, recently, studies within the ES literature increasingly consider potentially unsustainable uses of natural resources. To align ES research and decision-making with the overarching normative goal of sustainability, equity considerations should be put central in ES assessments, given that achieving inter- and intragenerational equity within ecological limits is the core goal of sustainability. Yet, the integration of distributional, recognitional and procedural equity issues in ES research and decision-making remains a challenge. Analyzing ES in a disaggregated way can be a tool to meet this challenge.

Disaggregation of ES can be understood as the assessment of ES by a particular theme, such as who benefits, in which ways, where, and when. This dissertation proposes to disaggregate ES along the four dimensions beneficiary groups, value types, space, and time, which are dimensions that are important for progress in ES research and decision-making, but remain under-researched. Three critical gaps with regard to ES disaggregation can be identified in the ES literature: (1) a systematic approach to disaggregating ES provision and appropriation is lacking, (2) empirical, disaggregated ES assessments remain scarce, and (3) research results are not integrated into decision-making due to lack of disaggregated results. To address these three gaps and to highlight the potential contributions of the disaggregation concept to ES research and decision-making, this dissertation addresses the following overarching research question: "*How can disaggregated analyses of ES help to better assess and address equity implications of ES provision and appropriation in both research and decision-making?*" More specifically, this dissertation formulates three research aims (RAs): (1) to explore theoretical and methodological approaches to ES disaggregation, (2) to empirically examine ES disaggregation along different dimensions in an Ethiopian case study region, and (3) to develop an approach to decision-making that integrates results of ES disaggregation.

This dissertation follows a place-based, social-ecological systems research approach using a case study in southwestern Ethiopia. This case study region is particularly suited to study equity implications connected to the provision and appropriation of ES, not only because of local people's dependency on ES and ongoing rapid social-ecological change, but also because previous research has already highlighted relevant existing equity issues. This dissertation encompasses both conceptual and empirical work. Whereas the conceptual work is based on a review of the existing literature as well as conceptual and methodological considerations, the empirical analyses rely mostly on two sets of data (an expert survey and a questionnaire with local people which were collected in the case study region in 2020 and 2021). In addition, ecological and social data of previous research projects in the case study region are incorporated. Diverse methods are employed to analyze the data, including descriptive statistics, hierarchical cluster analyses, correlation analyses, linear regression models, and chi-square tests of independence.

To address the gap of a missing systematic approach to ES disaggregation, new theoretical and methodological approaches to ES disaggregation are explored in this dissertation (RA1). It makes a foundational theoretical contribution, by defining what disaggregation means, introducing and discussing the four disaggregation dimensions that are central to this dissertation, and providing ideas for a systematic approach to disaggregation. Moreover, this dissertation shows that the four disaggregation dimensions beneficiary groups, value types, space, and time can indeed act as a useful lens to highlight distributional, recognitional, and procedural equity issues connected to ES delivery. Moreover, disaggregated analyses encourage the use of alternative methods and approaches, such as selecting ES based on local relevance and not according to pre-defined categories, using a coffee bean exercise as a participatory means to obtain disaggregated data, and using cluster analysis as an approach to reduce complexity.

Empirical, disaggregated ES assessments remain scarce in the ES literature. To exemplify how such disaggregated ES assessments can be conducted in practice, this dissertation empirically examines

ES disaggregation along different dimensions in an Ethiopian case study region (RA2). The empirical analyses highlight different equity issues by using the four disaggregation dimensions as a lens to the ES delivery process. The foci on flows/appropriation, values/benefits and beneficiary groups contribute to gaps in the ES literature, where the socioeconomic side of the ES delivery process is rarely assessed. Even so, the focus on distributional and recognitional equity in this dissertation mirrors the lack of consideration of procedural equity issues in the ES literature. Despite this drawback, the insights into recognitional equity gained through this dissertation can feed into governance and decision-making processes to improve procedural equity in the case study region. Through the assessment of ES by the four proposed disaggregation dimensions equity-focused, place-based understandings of the social-ecological system of the case study region are generated, with regard to the role of the social-ecological context, and the development of the case study region towards specialization and market integration.

To address the gap of lacking integration of ES research results into decision-making, this dissertation sets out to develop an approach to decision-making that integrates results of ES disaggregation (RA3). It explicitly presents a generalized, social-ecological approach to support land use decision-making, with six steps to generate and analyze scenarios of disaggregated, landscape-scale changes in land use and ES provision and appropriation. This dissertation also generates equity-related insights for decision-making in the case study region. Generally speaking, to enhance equitable decision-making in the case study region it is recommendable to apply context-specific management of kebeles (smallest administrative units in Ethiopia), to recognize heterogeneity in people's relationship with ES across space and between beneficiary groups, and to pay attention to the role of the social-ecological context, especially when it comes to planning for the management of future developments.

Following calls for necessary improvements in response to remaining gaps in ES research, especially regarding the integration of equity issues in ES assessments, this dissertation puts forward disaggregation as a tool to better assess and address equity issues in ES research and decision-making. The contributions of this dissertation ultimately help to align ES research and decision-making with equity, as well as with sustainability as an overarching normative goal. The results and insights derived in this dissertation can inspire future research. For example, an encompassing, systematic review of disaggregated studies could derive current foci and gaps in the literature to guide ES research in the future. Approaches and methods of this dissertation, such as using tokens to collect disaggregated data, can be transferred and tested in other case study regions. For the case study region in southwestern Ethiopia, future research could focus on better understanding intergenerational equity issues in terms of (un)sustainable ES flows, monitor the future development of the case study region, e.g. in terms of ES specialization and values, and look into how the results can be best communicated to local people and decision-makers, in order to ensure their uptake in decision-making.

Zusammenfassung

Ökosystemdienstleistungen (ÖSD) sind Leistungen, die Menschen aus ihren Interaktionen mit ökologischen Strukturen und Funktionen erhalten. Das Konzept der ÖSD ist eng mit Nachhaltigkeit verknüpft. In jüngster Zeit befassen sich Studien innerhalb der ÖSD-Literatur jedoch zunehmend mit der potenziell nicht-nachhaltigen Nutzung natürlicher Ressourcen. Um Forschung und Entscheidungsfindung rund um ÖSD mit dem übergeordneten normativen Ziel der Nachhaltigkeit in Einklang zu bringen, sollten Gerechtigkeitsüberlegungen in den Mittelpunkt von ÖSD-Bewertungen gestellt werden, da das Erreichen inter- und intragenerationeller Gerechtigkeit innerhalb ökologischer Grenzen das Kernziel von Nachhaltigkeit ist. Die Integration von Fragen der Verteilungs-, Anerkennungs- und Verfahrensgerechtigkeit in die ÖSD-Forschung und Entscheidungsfindung bleibt jedoch eine Herausforderung. Die disaggregierte Analyse von ÖSD kann eine Lösung für diese Herausforderung sein.

Die Disaggregierung von ÖSD kann als eine Begutachtung von ÖSD nach einem bestimmten Thema verstanden werden, z.B. wer, auf welche Weise, wo und wann profitiert. In dieser Dissertation wird vorgeschlagen, ÖSD anhand von vier Dimensionen (begünstigte Gruppen, Werttypen, Raum und Zeit) zu disaggregieren. Diese Dimensionen sind von hoher Relevanz für Fortschritte in der ÖSD-Forschung und Entscheidungsfindung, aber noch zu wenig erforscht. In der ÖSD-Literatur lassen sich drei kritische Lücken in Bezug auf die Disaggregierung von ÖSD ausmachen: (1) Es fehlt ein systematischer Ansatz zur Disaggregierung der Bereitstellung und Aneignung von ÖSD, (2) empirische, disaggregierte ÖSD-Bewertungen sind nach wie vor rar, und (3) Forschungsergebnisse werden aufgrund fehlender disaggregierter Ergebnisse nicht in die Entscheidungsfindung integriert. Um diese drei Lücken zu schließen und die potenziellen Beiträge des Konzepts der Disaggregierung zur ÖSD-Forschung und Entscheidungsfindung hervorzuheben, befasst sich diese Dissertation mit der folgenden übergreifenden Forschungsfrage: „*Wie können disaggregierte Analysen von ÖSD dazu beitragen, die Gerechtigkeits-Auswirkungen der Bereitstellung und Aneignung von ÖSD sowohl in der Forschung als auch in der Entscheidungsfindung besser zu beurteilen und zu berücksichtigen?*“ Konkret formuliert diese Dissertation drei Forschungsziele (FZ): (1) Erforschung theoretischer und methodischer Ansätze zur ÖSD-Disaggregierung, (2) empirische Untersuchung von ÖSD-Disaggregierung entlang verschiedener Dimensionen in einer äthiopischen Fallstudienregion, und (3) Entwicklung eines Ansatzes zur Entscheidungsfindung, der die Ergebnisse der ÖSD-Disaggregierung integriert.

Diese Dissertation verfolgt einen ortsbezogenen sozial-ökologischen Systemforschungsansatz in einer Fallstudienregion im Südwesten Äthiopiens. Die Region ist besonders geeignet, um die Auswirkungen der Bereitstellung und Aneignung von ÖSD auf Gerechtigkeit zu untersuchen: zum einen aufgrund der Abhängigkeit der Menschen vor Ort von ÖSD und einem anhaltenden raschen sozial-ökologischen Wandel, zum anderen, weil frühere Forschungsergebnisse bereits relevante bestehende Gerechtigkeitsprobleme in der Fallstudienregion aufgezeigt haben. Diese Dissertation umfasst sowohl konzeptionelle als auch empirische Arbeiten. Während die konzeptionelle Arbeit auf einer Sichtung der vorhandenen Literatur sowie auf konzeptionellen und methodischen Überlegungen beruht, stützen sich die empirischen Analysen hauptsächlich auf zwei Datensätze (eine Expert*innenbefragung und ein Fragebogen mit der lokalen Bevölkerung, die in den Jahren 2020 und 2021 in der Fallstudienregion durchgeführt wurden). Darüber hinaus werden ökologische und soziale Daten aus früheren Forschungsprojekten in der Fallstudienregion einbezogen. Zur Analyse der Daten werden verschiedene Methoden eingesetzt, darunter deskriptive Statistiken, hierarchische Clusteranalysen, Korrelationsanalysen, lineare Regressionsmodelle und Chi-Quadrat-Tests auf Unabhängigkeit.

Um die Lücke eines fehlenden systematischen Ansatzes zur ÖSD-Disaggregierung zu schließen, werden in dieser Dissertation neue theoretische und methodische Ansätze zur ÖSD-Disaggregierung erforscht (FZ1). Die Dissertation leistet somit einen grundlegenden theoretischen Beitrag, indem sie (1) definiert, was Disaggregierung bedeutet, (2) die vier Disaggregierungs-Dimensionen

einführt und erörtert, die für diese Dissertation von zentraler Bedeutung sind, und (3) Ideen für einen systematischen Ansatz zur Disaggregierung liefert. Darüber hinaus zeigt diese Dissertation, dass die vier Disaggregierungs-Dimensionen (begünstigte Gruppen, Werttypen, Raum und Zeit) tatsächlich als nützliche Perspektive fungieren können, um Verteilungs-, Anerkennungs- und Verfahrensgerechtigkeitsprobleme im Zusammenhang mit der Bereitstellung von ÖSD zu beleuchten. Darüber hinaus fördern disaggregierte Analysen die Verwendung alternativer Methoden und Ansätze, wie die Auswahl von ÖSD in Bezug auf deren lokale Relevanz statt nach vordefinierten Kategorien, die Verwendung einer Kaffeebohnenübung als partizipatives Mittel zur Gewinnung disaggregierter Daten, und die Verwendung von Clusteranalysen als Ansatz zur Reduktion von Komplexität.

Empirische, disaggregierte ÖSD-Bewertungen sind in der ÖSD-Literatur nach wie vor Mangelware. Daher wurde in dieser Dissertation ÖSD-Disaggregierung anhand verschiedener Dimensionen in einer äthiopischen Fallstudienregion empirisch untersucht (FZ2). Die empirischen Analysen beleuchten verschiedene Gerechtigkeitsaspekte, indem sie die vier Disaggregierungs-Dimensionen als Perspektive für den ÖSD-Bereitstellungsprozess verwenden. Die Schwerpunkte auf Ströme/Aneignung, Werte/Nutzen und begünstigte Gruppen tragen zur Schließung von Lücken in der ÖSD-Literatur bei, während der Schwerpunkt auf Verteilungs- und Anerkennungsgerechtigkeit die mangelnde Berücksichtigung von Verfahrensgerechtigkeitsthemen widerspiegelt. Trotz dieses Nachteils können die in dieser Dissertation gewonnenen Erkenntnisse zur Anerkennungsgerechtigkeit in Entscheidungsprozesse einfließen, um die Verfahrensgerechtigkeit in der Fallstudienregion zu verbessern. Durch die Begutachtung der ÖSD anhand der vier vorgeschlagenen Disaggregierungs-Dimensionen wird ein gerechtigkeitsorientiertes, ortsbezogenes Verständnis des sozial-ökologischen Systems der Fallstudienregion abgeleitet, und zwar im Hinblick auf die Rolle des sozial-ökologischen Kontexts und die Entwicklung der Fallstudienregion in Richtung Spezialisierung und Marktintegration.

Um das Problem der mangelnden Integration von ÖSD-Forschungsergebnissen in die Entscheidungsfindung anzugehen, wurde in dieser Dissertation ein Ansatz zur Entscheidungsfindung entwickelt, der Ergebnisse von ÖSD-Disaggregierung integriert. Es wird explizit ein verallgemeinerter, sozial-ökologischer Ansatz zur Unterstützung der Entscheidungsfindung bei der Landnutzung vorgestellt. Dieser umfasst sechs Schritte zur Erstellung und Analyse von Szenarien disaggregierter, landschaftsbezogener Veränderungen bei der Landnutzung und der Bereitstellung und Aneignung von ÖSD. Diese Dissertation liefert zudem gerechtigkeitsrelevante Erkenntnisse für die Entscheidungsfindung in der Fallstudienregion. Generell ist es für eine gerechtere Entscheidungsfindung empfehlenswert, ein kontextspezifisches Management der Kebeles (kleinste Verwaltungseinheiten in Äthiopien) anzuwenden, die Heterogenität der Beziehung von Menschen zu ÖSD anzuerkennen, und die Rolle des sozial-ökologischen Kontextes zu berücksichtigen, insbesondere wenn es um die Planung des Managements zukünftiger Entwicklungen geht.

Als Reaktion auf Forderungen nach notwendigen Verbesserungen in Bezug auf verbleibende Lücken in der ÖSD-Forschung, insbesondere in Bezug auf die Integration von Gerechtigkeitsaspekten in ÖSD-Bewertungen, wird in dieser Dissertation Disaggregierung als ein Instrument zur besseren Beurteilung und Berücksichtigung von Gerechtigkeitsaspekten in der ÖSD-Forschung und Entscheidungsfindung vorgestellt. Diese Dissertation kann dabei helfen, die ÖSD-Forschung und Entscheidungsfindung auf Gerechtigkeit sowie auf Nachhaltigkeit als übergreifendes normatives Ziel auszurichten. Trotz ihrer Beiträge lassen die in dieser Dissertation gewonnenen Ergebnisse und Erkenntnisse Raum für zukünftige Forschung. Zum Beispiel kann eine umfassende, systematische Übersicht von disaggregierten Studien aktuelle Schwerpunkte und Lücken in der Literatur aufzeigen, um zukünftige Forschung besser auszurichten. Ansätze und Methoden dieser Dissertation, wie z.B. die Verwendung von Spielsteinen zur Erhebung disaggregierter Daten, können auf andere Fallstudienregionen übertragen und in diesen erprobt werden. Für die Fallstudienregion im Südwesten Äthiopiens kann sich die zukünftige Forschung darauf konzentrieren, Fragen der intergenerationellen Gerechtigkeit in Bezug auf (un)nachhaltige ÖSD-Ströme besser zu verstehen, und

die zukünftige Entwicklung der Fallstudienregion zu beobachten, z. B. in Bezug auf ÖSD-Spezialisierung und damit verbundene Werte. Zusätzlich interessant wäre es, zu untersuchen, wie Forschungsergebnisse am besten an die lokale Bevölkerung und Entscheidungsträger*innen kommuniziert werden können, um sicherzustellen, dass sie in die Entscheidungsfindung einfließen.

Preface

This dissertation is presented as a series of manuscripts. With the exception of Chapter I (the framework chapter), all chapters are designed to be stand-alone articles and are either published (Chapters II and III), or submitted for publication (Chapters IV and V, Appendix I) in international, peer-reviewed scientific journals. Appendix II has been published as an open-access booklet. Due to the requirements of the individual journals, stylistic and formatting differences (also with regard to the references and appendices) are possible between the chapters. The content of each published chapter is the same as the published article, and they are included in their original format as they appear in the journals. The submitted chapters are formatted similarly to Chapter I (the framework chapter). On the title page of each published or submitted chapter, a list of the co-authors as well as the explicit reference to the published article (if published), or the publication status and the respective journal (if submitted), are indicated.

This dissertation puts forward disaggregation as a tool to better assess and address equity issues in ecosystem services research and decision-making. Chapter I is the framework chapter of this dissertation. It introduces the overarching motivation and research question, and, by summarizing and synthesizing the four individual chapters, highlights the contributions of this dissertation to the ecosystem services literature. Chapter II is the conceptual basis for this dissertation, Chapters III and IV are empirical studies and focus on different dimensions of disaggregation, whereas Chapter V is both a conceptual and empirical study, with a focus on decision-making. One additional co-authored publication (Appendix I) and a policy booklet (Appendix II) are based on the same case study region as the empirical chapters of this dissertation. They thus provide additional valuable insights and background information to this dissertation.

List of publications

The following list includes the four research publications that contribute to this dissertation, referred to as Chapters II-V. Chapter I is the framework chapter of this dissertation and thus not included in the list. Appendix I and II are based on same case study region as the empirical chapters of this dissertation, providing additional valuable contributions and background information to this dissertation.

Chapter II: **Brück, M.**, D. J. Abson, J. Fischer, and J. Schultner. 2022. Broadening the scope of ecosystem services research: Disaggregation as a powerful concept for sustainable natural resource management. Ecosystem Services 53:101399. doi: 10.1016/j.ecoser.2021.101399.

Chapter III: **Brück, M.**, J. Fischer, E. Law, J. Schultner, and D. Abson. 2023. Drivers of ecosystem service specialization in a smallholder agricultural landscape of the Global South: a case study in Ethiopia. Ecology and Society 28(3). doi: 10.5751/ES-14185-280301.

Chapter IV: **Brück, M.**, J. Schultner, B. B. Negash, F. D. Damu, and D. J. Abson. Plural valuation in southwestern Ethiopia: Disaggregated ecosystem service values in a smallholder landscape: *Major revisions with People and Nature.*

Chapter V: **Brück, M.**, F. Benra, D. W. Duguma, J. Fischer, T. S. Jiren, E. Law, M. Pacheco-Romero, J. Schultner, and D. J. Abson. A social-ecological approach to equitable land use decision making: *Under Review in Ambio.*

Appendix I: Duguma, D. W., **M. Brück**, G. Shumi, E. Law, F. Benra, J. Schultner, S. Nemomissa, D. J. Abson, and J. Fischer. Future ecosystem service provision under land-use change scenarios in southwestern Ethiopia: *Under Review in Ecosystems and People.*

Appendix II: Jiren, T. S., D. J. Abson, **M. Brück**, J. Fischer, and J. Hanspach. 2023. A shared vision for the landscapes of southwestern Ethiopia, Sofia. [online] URL: https://books.pensoft.net/books/13390.

Chapter I: Assessing equity implications of the provision and appropriation of ecosystem services through disaggregation (Framework chapter)

1. Introduction

Ecosystem services (ES) are the benefits that humans obtain from nature and which ultimately contribute to human well-being (Millennium Ecosystem Assessment 2005; Haines-Young and Potschin 2010). The ES concept has strong links to the notion of sustainability, and yet, recently, studies within the ES literature increasingly consider potentially unsustainable uses of natural resources (Abson et al. 2014; Schröter et al. 2017). In a sustainability context, inter- and intragenerational equity issues should be explicitly considered, also for studies on ES, seeing that the core goal of sustainability is to achieve equity within ecological limits (World Commission on Environment and Development 1987; Schröter et al. 2017). Nonetheless, explicit incorporation of equity issues remains a challenge in ES research and decision-making, despite recent developments, which have begun to recognize the importance of distributional equity issues in particular (Langemeyer and Connolly 2020; Loos et al. 2022). To make further progress, ES can be analyzed in a disaggregated way, allowing to better assess and address equity issues in research and decision-making (Daw et al. 2011; Mandle et al. 2020). In this dissertation, I define ES disaggregation, or the disaggregated analysis of ES, as an assessment of ES by a particular theme – such as who benefits, from which particular values, where and when.

To highlight the usefulness of the disaggregation concept to ES research and decision-making, this dissertation sets out to understand *how* disaggregated analyses of ES can help to better assess and address equity implications of ES provision and appropriation. In particular, it addresses three critical gaps with regard to ES disaggregation in research and decision-making: (1) a systematic approach to ES disaggregation is missing, (2) empirical disaggregated ES assessments remain scarce, and (3) research results are not integrated into decision-making due to lack of disaggregated results. In this framework chapter, I first shortly review the literature around ES, equity and disaggregation, and derive the three gaps which will be addressed in this dissertation. I then introduce the overarching research question of this dissertation as well as three specific research aims, which will be addressed in the four subsequent chapters (II – V). In the following sections of this chapter, I will first explain the research approach of this dissertation (section 2), and then present key findings and contributions of Chapters II to V (section 3). Finally, I synthesize all findings into four key insights (section 4), before giving an outlook for future research (section 5).

1.1 Motivation and key concepts

The **ES concept** provides a framework for linking ecological structures and functions to human well-being (Haines-Young and Potschin 2010). Until now, it has developed from a metaphor about humans' dependence on nature (Ehrlich and Ehrlich 1981; Ehrlich and Mooney 1983; Daily 1997) to a dominant discourse in sustainability science (Abson et al. 2014; Costanza et al. 2017; Schröter et al. 2017). In a decision-making context, the ES concept has provided important arguments regarding the importance of nature to human well-being (Costanza et al. 1997; Chaplin-Kramer et al. 2019), and laid the foundation for influential governance tools, such as payments for ES (Daily and Matson 2008; Gómez-Baggethun et al. 2010).

Despite intensive research and development, the concept has been criticized, for example, for the failure to recognize pluralistic understandings of human-nature relationships (with regard to knowledge systems and values), or the limited explicit consideration of intra- and intergenerational equity issues (Norgaard 2010; Bennett et al. 2015; Rieb et al. 2017; Díaz et al. 2018; Kadykalo et al. 2019; Mandle et al. 2020). As a result, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) proposed the concept of "nature's contributions to people (NCP)" as a further development of the ES concept, which tries to address these issues (Díaz et al. 2015; Díaz et al. 2018). However, this initiative has also been criticized, among other things, for introducing new terminology where an attempt to reform the concept might have been more appropriate, especially seeing that aspects claimed as novel to NCP are already captured in the ES literature (Kenter 2018; Maes et al. 2018; Kadykalo et al. 2019). Acknowledging the complementarity of the ES and NCP concepts (Peterson et al. 2018; Kadykalo et al. 2019), for conceptual clarity,

in this dissertation, I use the term "ecosystem services" to refer to the benefits received by humans from their interactions with ecological structures and functions.

The process from ecosystems and their ecological functions to ES that are appropriated by humans and hence provide a benefit – **the ES delivery process** – has been described in different ways, using a variety of terminology (Haines-Young and Potschin 2010; Villamagna et al. 2013; Burkhard et al. 2014; Spangenberg et al. 2014). In this dissertation, following Burkhard et al. (2014), Schröter et al. (2017), and Primmer et al. (2015), I use the following terms to describe the process of ES delivery:

- ecosystem properties (a set of ecological structures, processes, and functions, based on different land covers) have the capacity to potentially provide ES,
- which can (together with additional inputs in the form of different types of capitals) in turn be appropriated by humans as flows (at different spatial scales in relation to where the ecological function originates),
- to which humans ascribe multiple types of values and hence obtain benefits, which contribute to human well-being; such that ultimately,
- ES decision-making (or governance) is informed by and influences all stages of this process.

The ES concept has strong links to the notion of sustainability, but recently, studies within the ES literature increasingly focus on potentially unsustainable uses of natural resources (Abson et al. 2014; Schröter et al. 2017). **Sustainability** is defined as a state that meets the needs of current and future human generations within ecological limits (World Commission on Environment and Development 1987). When ES assessments consider appropriation beyond carrying capacities, or produce only aggregated values, the *ES concept comes into conflict with the core goal of sustainability*, i.e. achieving inter- and intragenerational equity within ecological limits (World Commission on Environment and Development 1987; Schröter et al. 2017). From a social-ecological systems (SES) perspective, sustainability and equity are deeply interlinked, and can be understood as intertwined drivers and outcomes of coupled systems dynamics (Leach et al. 2018). Consequently, to align the ES concept with sustainability as an overarching normative goal, conceptualization and management of ES should explicitly consider inter- and intragenerational equity issues (Schröter et al. 2017).

Equity has mostly been thought of as **distributional, procedural and recognitional equity** (Schlosberg 2007; Fraser 2009; Leach et al. 2018; Loos et al. 2022). Distributional equity refers to how resources, costs and benefits are allocated or shared amongst people and groups. Specifically, in the context of ES, distributional equity is concerned with how costs and benefits of nature are distributed between different groups of beneficiaries, e.g. how changes in ES supply or access positively or negatively affect different groups (Dorresteijn et al. 2017; Schultner et al. 2021; Felipe-Lucia et al. 2022). Recognitional equity regards the consideration of and respect for different values, identities, rights and preferences of different social groups. In the context of ES, this means to understand and represent different worldviews, opinions and values with regards to nature and ES, e.g. by considering how different stakeholders perceive ES and human-nature relationships (Martín-López et al. 2014; Arias-Arévalo et al. 2017). Procedural equity is concerned with who is involved (and how) in decision-making and political processes. Likewise, in the context of ES, procedural equity focuses on the participation of all stakeholders and rights holders in ES interventions, and their power and roles in decision-making around ES, e.g. through analyzing how different stakeholders are involved in ES governance (Felipe-Lucia et al. 2015; Jiren et al. 2022). *Explicit incorporation of such equity issues in ES research and decision-making remains a challenge*, despite recent developments, which have however largely been focused on distributional equity (Langemeyer and Connolly 2020; Loos et al. 2022).

In order to ensure better integration of equity issues in ES research and decision-making, ES can be analyzed in a disaggregated way (Daw et al. 2011; Brooks et al. 2014; Mandle et al. 2020). In this

dissertation, I define **ES disaggregation,** or the disaggregated analysis of ES, as an assessment of ES by a particular theme – such as who benefits, from which particular values, where and when. In other words, ES disaggregation can be understood as the process of understanding the multiple, interdependent dimensions across which the various benefits of ES are appropriated and distributed. In contrast to dominant, biophysical approaches in the ES literature, which distinguish different types or categories of ES (Millennium Ecosystem Assessment 2005; Fisher et al. 2009), I focus here on a more social type of disaggregation. With this intention, I propose to disaggregate ES along the **four dimensions beneficiary groups, value types, space and time**, which are dimensions that are important for progress in ES research and decision-making, but remain underresearched (Bennett et al. 2015; Mandle et al. 2020).

Aggregate assessments of ES can be useful under certain circumstances, because they emphasize the overall importance of ES to decision-makers (Costanza et al. 1997; Costanza et al. 2014). Nonetheless, they fail to explicitly recognize equity issues among beneficiary groups, value types, locations or different points in time, and thus potentially over-simplify the relationship between ES and human well-being (Daw et al. 2011). In fact, changes in ES provision and appropriation and trade-offs among services can create winners and losers, even if aggregate well-being derived from ES increases (Rodriguez et al. 2006; Carpenter et al. 2009; Cord et al. 2017). In contrast, the four proposed dimensions of ES disaggregation can help to assess and address different equity issues. For instance, the disaggregation by beneficiary groups is useful in identifying mainly distributional equity issues, but, through recognition of power and governance questions, can also address recognitional and procedural equity issues related to the provision and appropriation of ES (Daw et al. 2011; Martín-López et al. 2012; Felipe-Lucia et al. 2015; Martín-López et al. 2019). Equally important, disaggregation by value types can help to recognize the plurality of values, preferences and worldviews (Arias-Arévalo et al. 2017; Zafra-Calvo et al. 2020; Beery et al. 2021; Pascual et al. 2023). Furthermore, spatial disaggregation mainly helps to address questions of distributional equity (Hein et al. 2006; Liu et al. 2013; Schröter et al. 2018), and temporal disaggregation can help to understand intergenerational distributional equity issues (Hein et al. 2016; Rau et al. 2018; Rau et al. 2019).

1.2 Research question and aims

To highlight the usefulness and potential contributions of the disaggregation concept to ES research and decision-making, this dissertation addresses the following overarching research question:

How can disaggregated analyses of ES help to better assess and address equity implications of ES provision and appropriation in both research and decision-making?

Three gaps can be identified in the ES literature with regard to theory and methodology, empirics, and decision implementation of ES disaggregation. In order to address these gaps, this dissertation formulates three research aims, which are in turn addressed in four different chapters (Figure 1).

The first gap is that, to date, *a systematic approach to disaggregating ES provision and appropriation is lacking.* In a seminal paper, Daw et al. (2011) were the first to conceptually highlight the usefulness of disaggregated analyses of ES, which they illustrated via coastal examples from developing countries. In the same way, some examples of conceptual approaches in the ES literature contribute to a more informed theoretical understanding of, and methodological approach to, ES disaggregation, with regard to beneficiary groups (Reed et al. 2013; Fisher et al. 2014; Felipe-Lucia et al. 2015; Martín-López et al. 2019; Robinson et al. 2019), value types (Chan et al. 2012; Martín-López et al. 2014; Pascual et al. 2017; Pascual et al. 2023), space (Bagstad et al. 2013; Liu et al. 2013; Schröter et al. 2018) and time (Hein et al. 2016; Rau et al. 2018). In spite of these contributions, an encompassing, systematic approach to disaggregating ES provision and appropriation does not exist until now. Hence, the first research aim (RA1) of this dissertation is **to explore theoretical and methodological approaches to ES disaggregation**, for the purpose of contributing to a more thorough understanding of the usefulness of ES disaggregation itself, and of connected suitable methods and

approaches. RA1 is mainly addressed by Chapter II, which is a conceptual study and aims to strengthen the position of disaggregation in ES research and decision-making, by providing a systematic approach to ES disaggregation.

The second gap is that many empirical ES assessments to date are aggregate assessments, and that *disaggregated approaches remain scarce* (Suich et al. 2015; Cruz-Garcia et al. 2017; Blythe et al. 2019; Mandle et al. 2020). A recent structured review by Mandle et al. (2020) found that 31% of ES assessments disaggregated spatially, but only few assessments (7%) disaggregated by beneficiary groups, and mediating factors that affect benefit delivery (such as infrastructure, vulnerabilities, substitute availability, or ability to access ES) were only considered in 35% of assessments. The second research aim (RA2) of this dissertation therefore is **to empirically examine ES disaggregation along different dimensions in an Ethiopian case study region**, in order to add empirical examples of disaggregated ES assessments to the literature, which show their general and case-specific usefulness in highlighting equity implications connected to ES delivery. Chapters III and IV are empirical studies, conducted in a case study region in southwestern Ethiopia, and mainly address this second research aim. The case study region in southwestern Ethiopia is particularly suited to study equity issues connected to the provision and appropriation of ES (see section 2.3). With this intention, Chapter III analyzes potential drivers of agricultural specialization in the case study region, with a particular focus on telecoupling (socioeconomic and environmental interactions among coupled human and natural systems over distances; Liu et al. 2013) and comparative advantage. Chapter IV assesses how rankings of ES (according to their general importance in people's lives) relate to people's individual characteristics, their social-ecological context, and the types of values they ascribe to each ES.

The third gap persists between the desire of ES research to inform decisions, and the actual *limited uptake of research results in decision-making* (Olander et al. 2017; Mastrángelo et al. 2019; Mandle et al. 2020). Increasing the decision relevance of ES research requires the consideration of equity issues, through disaggregating benefits among different groups, measuring different types of values, and understanding spatial patterns and temporal dynamics of ES (Bennett et al. 2015; Mandle et al. 2020; Loos et al. 2022). The third research aim (RA3) of this dissertation is thus **to develop an approach to decision-making that integrates results of ES disaggregation**, in order to show how disaggregated approaches can generate useful, equity-focused insights for decision-making. RA3 is mainly addressed by Chapter V, which is both a conceptual and an empirical study, with a focus on decision-making, and presents a social-ecological approach to support land use decision-making, and its application to the case study region.

Filling these three gaps —lack of a systematic approach to ES disaggregation, dearth of disaggregated empirical ES assessments, and poor integration of research results into decision-making— is critical to establish disaggregation as a useful contribution to the ES literature, which helps to better address equity issues, and to ultimately (re-)align the ES concept with sustainability. To fill the three gaps and address the corresponding aims, this framework chapter synthesizes the findings and contributions of the four individual chapters of this dissertation into four key insights, which, on the whole, answer the overarching research question.

In section 2, I present the research approach of this dissertation, including the case study region, and give an overview of the aims and methods of each individual chapter. Section 3 summarizes the key findings and contributions of each chapter, before synthesizing the results and contributions across all chapters into four key findings in section 4. Finally, I give an outlook for future research in section 5.

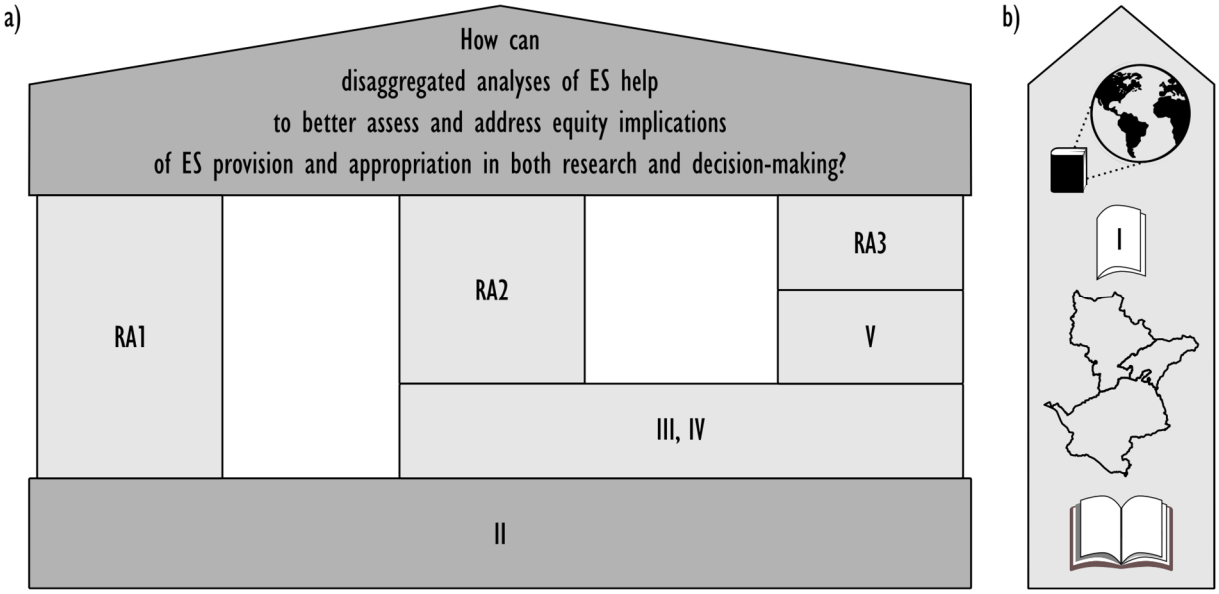

Figure 1. Logical flow of this dissertation. (a) The overarching research question of this dissertation was to understand how ES disaggregation can support the better integration of equity issues into ES research and decision-making. This overarching research question is addressed through three research aims. Research aim one (RA1) "to explore theoretical and methodological approaches to ES disaggregation" is mainly addressed by Chapter II, which also forms the conceptual basis for all other chapters. The second research aim (RA2) "to empirically examine ES disaggregation along different dimensions in an Ethiopian case study region" is mainly addressed by Chapters III and IV, which both contribute to Chapter V. Research aim three (RA3) "to develop an approach to decision-making that integrates results of ES disaggregation" is mainly addressed by Chapter V. (b) Both the conceptual work and the empirical work in the case study region are synthesized in this framework chapter (Chapter I), in order to contribute to both ES research and decision-making.

2. Research approach

In this section, I first give some background information on the research projects that this dissertation is based on (section 2.1). Then, I introduce the place-based, SES approach that this dissertation follows (2.2), and explain why the case study region is particularly suited to assess equity implications connected to the ES delivery process (2.3). Finally, I give an overview of the chapters of this dissertation, including their respective aims and methods (2.4).

2.1 Background

This dissertation was developed as part of the research project "Towards a Sustainable Bioeconomy: A Scenario Analysis for the Jimma Coffee Landscape in Ethiopia (ETH-Coffee)", which aimed to identify environmental and socioeconomic outcomes of ES flows in an increasingly teleconnected agricultural economy in southwestern Ethiopia. This ETH-Coffee project built on previous research work —the project "Identifying Social-Ecological System Properties Benefitting Biodiversity and Food Security (SESyP)"— which produced four plausible future scenarios for the case study region in 2040 (Jiren et al. 2020b). The four scenarios described two gradients, one from a focus on cash crops to a focus on food crops, and one from integrated land uses to segregated and intensified land uses.

Next to the results presented in this dissertation, results of the ETH-Coffee project include spatially explicit mappings of land use and land cover (LULC), biodiversity and ES under the four scenarios (Duguma et al. Under Review in Ecosystems and People; Duguma et al. Under Review in Communications Earth & Environment; Duguma et al. 2022; Duguma et al. 2023), assessments of stakeholder constellations under the four scenarios, as well as a study of stakeholder priorities for

the future development of the landscape (Jiren et al. 2022; Jiren et al. 2023b). Another key output was a policy booklet reporting the outcomes of a local stakeholder visioning process, which identified a widely shared vision for the future of the landscape (Jiren et al. 2023a). In addition to two sets of newly collected data, this dissertation also draws on data and results of the SESyP and the ETH-Coffee projects (see section 2.4).

2.2 Placed-based, social-ecological systems approach

In this dissertation, I follow a place-based, SES approach in a case study region in southwestern Ethiopia. Understanding SES as interdependent and linked systems of people and nature, which are nested across scales (Fischer et al. 2015), the SES approach provides a framework for understanding and analyzing interlinked dynamics of environmental and societal change, and highlights humanity's dependence on nature (Berkes et al. 1998; Anderies et al. 2004; Ostrom 2009; Fischer et al. 2015; Colding and Barthel 2019). Moreover, place-based research addresses the particular social-ecological dynamics of a system (specific cities, landscapes, seascapes or coastal regions), with an interest in understanding and identifying solutions for real-world problems (Carpenter et al. 2012; Fischer et al. 2014; Norström et al. 2022). A placed-based SES approach, focused on a case study region in southwestern Ethiopia, is appropriate for addressing the research question and aims of this dissertation, because sustainability and equity dynamically interact in SES (Leach et al. 2018), and because the case study region in southwestern Ethiopia is particularly suited to the study of equity issues connected to ES (see details in section 2.3).

2.3 Case study region

The case study region in southwestern Ethiopia is particularly suited to the study of equity issues connected to the provision and appropriation of ES, not only because of local people's dependency on ES and ongoing rapid social-ecological change, but also because previous research has already highlighted relevant existing equity issues in the case study region. Among other aims, this dissertation seeks to provide additional and more detailed assessments of equity issues connected to the ES delivery process in the case study region (RA2).

The case study region consists of three woredas (districts) in Jimma Zone, Oromia Region, southwestern Ethiopia, with a total area of about 2800 km² (Figure 2). The three woredas are further subdivided into 78 kebeles (smallest administrative units in Ethiopia). The landscape is a recognized biodiversity hotspot (Mittermeier et al. 2011), and characterized by a mosaic of farmland and moist evergreen Afromontane forest (Hylander et al. 2013). As a result, it provides both local and global benefits to people: Local smallholders are dependent on nature, and ES are important for subsistence and income generation (Shumi et al. 2019; Schultner et al. 2021), but also provide benefits of global importance, such as biodiversity (Beenhouwer et al. 2016). Due to different social, demographic, economic, environmental, technological, political and governance drivers (such as population growth and climate change), the landscape is undergoing rapid social-ecological change (Jiren et al. 2020b). In particular, livelihood strategies have traditionally been diversified and subsistence-oriented (Manlosa et al. 2019c). However, specialization and market integration are strongly encouraged by the government, and many stakeholders, such as farmers and representatives of governmental, non-governmental and civil society organizations, expect or even favor such developments (Federal Democratic Republic of Ethiopia, National Planning Commission 2016; Jiren et al. 2020a; Jiren et al. 2020b). Notably, over the past decades, production has already started to shift from subsistence to marketed crops, and access to cash crops with indirect benefits increased (Schultner et al. 2021).

According to local stakeholders, equity is an important uncertain and uncontrollable driver of change in the future (Jiren et al. 2020b). Indeed, under some future trajectories, high degrees of distributional inequity were expected among local people, e.g. due to the fact that some, especially poor, people may be unable to seize the opportunities of market integration (Jiren et al. 2020b). Additional previous research has highlighted relevant existing distributional, recognitional and procedural equity issues in the case study region. For example, local smallholders were highly

heterogeneous in their benefit-cost outcomes with regard to forest ES and disservices (Dorresteijn et al. 2017), in their ES-based livelihood strategies and underlying capital assets (Manlosa et al. 2019c), and in their access to emerging market-oriented services with indirect benefits (Schultner et al. 2021). Equally important, women's agency with regard to livelihoods and food security was highly restricted compared to men's, as well as their ability to participate, and hence being recognized, in community dialogues or public activities (Manlosa et al. 2019b; Manlosa 2022). What is more, preferences with regard to land use strategies and food security governance varied not only between stakeholder groups, but also within groups, for example, between relatively wealthy and poor smallholder farmers (Jiren et al. 2018b; Jiren et al. 2020a). In addition, the role of farmers in land governance in the study area was limited, and was restricted by limited tenure security and land use rights (Shumi et al. 2019; Manlosa 2022). In particular, governance related to ES was often strongly hierarchical, and dominated by government administrative organizations, which can lead to power capture, where the interests of a few powerful stakeholders override those of smallholder farmers (Jiren et al. 2018a; Jiren et al. 2022).

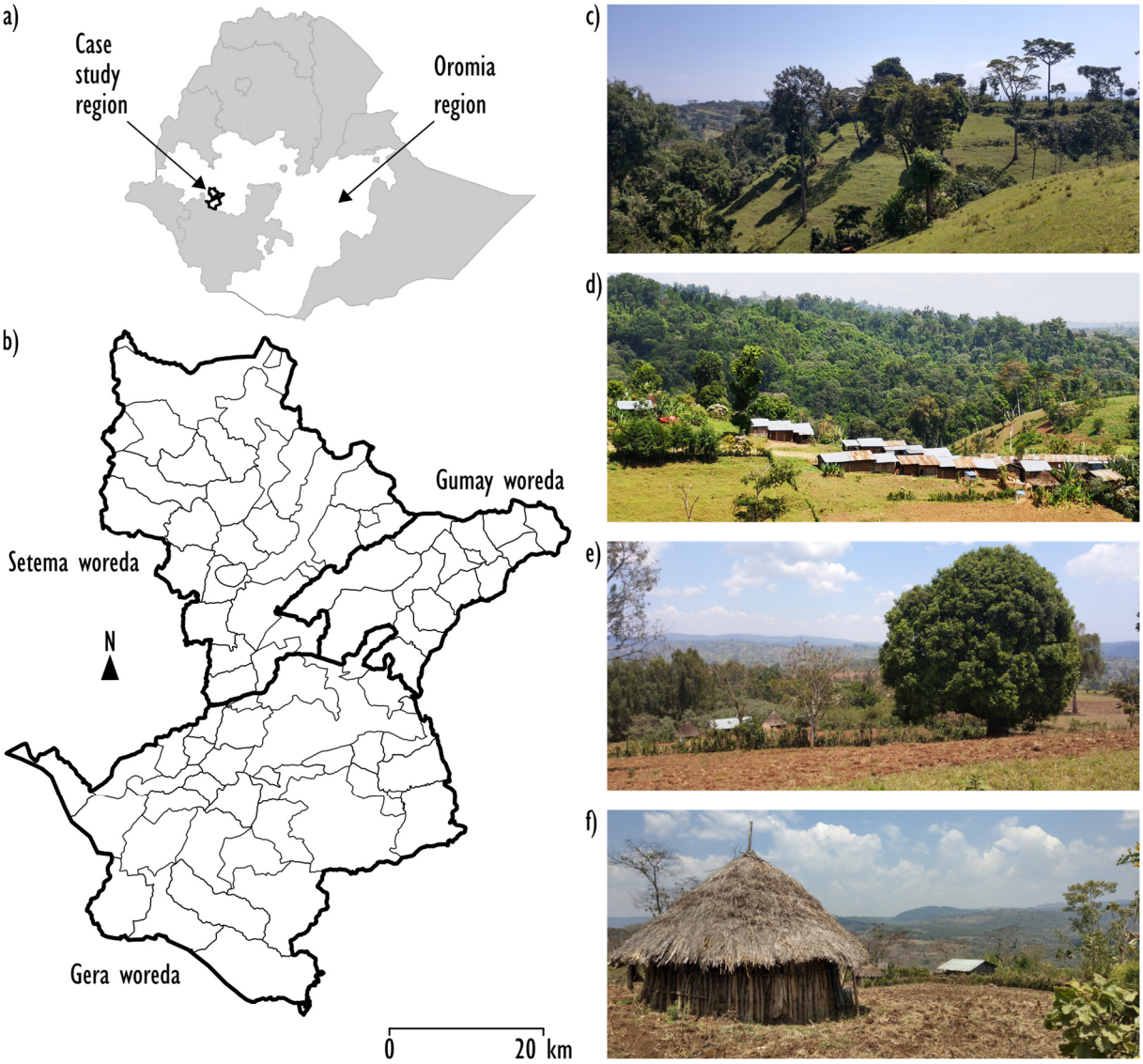

Figure 2. Maps and pictures of the case study region. (a) The case study region is situated in Jimma Zone, Oromia Region, southwestern Ethiopia, with a total area of about 2800 km². (b) It consists of three woredas (districts), which are further subdivided into 78 kebeles (smallest administrative units in Ethiopia). (c-f) The landscape is a recognized biodiversity hotspot and characterized by a mosaic of farmland and moist evergreen Afromontane forest.

2.4 Chapter overview

This section presents an overview of the aims and methods of Chapters II to V, and explains how the individual chapters connect to each other (Figure 3). This dissertation encompasses both conceptual (Chapters II and V) and empirical (Chapters III, IV and V) work. The empirical analyses rely mostly on two sets of data, one expert survey and one questionnaire with local people, collected in the case study region in 2020 and 2021.[1]

Chapter II: Broadening the scope of ecosystem services research: Disaggregation as a powerful concept for sustainable natural resource management

Chapter II is a conceptual study and mainly addresses RA1 "To explore theoretical and methodological approaches to ES disaggregation". The chapter aimed to strengthen the position of disaggregation in ES research and decision-making, by providing a systematic approach to disaggregation. Based on a review of the existing literature as well as conceptual and methodological considerations, I highlighted four equity issues that remain hidden in aggregate ES assessments. I then suggested and discussed four disaggregation dimensions (beneficiary groups, value types, space, and time) that can address these issues. In addition, I presented a generally applicable, structured approach to assessing ES in a disaggregated way, and, in conclusion, looked more closely at the role of disaggregated analyses in decision-making. Chapter II is the conceptual basis of this dissertation, and hence informed all other chapters.

Chapter III: Drivers of ecosystem service specialization in a smallholder agricultural landscape of the Global South: a case study in Ethiopia

Chapter III is an empirical study, conducted in the case study region in southwestern Ethiopia, and mainly addresses RA2 "To empirically examine ES disaggregation along different dimensions". In this chapter, I analyzed potential drivers of agricultural specialization in the case study region, with a particular focus on telecoupling and comparative advantage. Data on production and flows of eight locally relevant ES for 61 multifunctional kebeles were collected though expert surveys in woreda offices in October and November 2020. For ES production, official data or experts' estimates were collected, whereas ES flows were elicited through a participatory "coffee bean exercise" (allocation of 20 coffee beans to five spatial scales). To analyze the relationships between specialization, telecoupling and comparative advantage (the main variables of interest), I used hierarchical cluster analysis, correlation analysis, and a linear regression model. First, indices based on ES production and flow data were defined to quantify specialization, telecoupling and comparative advantage in each kebele. Second, correlations between these main variables were examined by the Kendall rank correlation coefficient across all kebeles, and for three farming type clusters, which were derived through a hierarchical cluster analysis based on ES production data. Lastly, I used a linear regression model with specialization as dependent variable to statistically test the role of telecoupling and comparative advantage, and other social and biophysical variables, as possible drivers of specialization. Data and results of this chapter are partly integrated into Chapter V.

Chapter IV: Plural valuation in southwestern Ethiopia: Disaggregated ecosystem service values in a smallholder landscape

Chapter IV is an empirical study conducted in the case study region, and also mainly addresses RA2 "To empirically examine ES disaggregation along different dimensions". This chapter assessed how rankings of ES (according to their general importance in people's lives) relate to people's individual characteristics, their social-ecological context, and the types of values they ascribe to each ES. To investigate the role of the social-ecological context, kebeles in the case study region were clustered into four social-ecological kebele archetypes (also referred to as social-ecological kebele groups), based on a range of ecological and social variables. The pasture-cropland, the khat-cropland, the woody vegetation and the accessible-wealthy archetype were characterized,

[1] The data collection thus took place in the middle of the COVID-19 pandemic. It was organized remotely and the data collection itself was conducted by two colleagues who live and work close to the case study region. Measures were taken to protect them and others from COVID-19.

respectively, by high availability of pasture and arable land, by high availability of khat (a popular plant stimulant) and arable land, by high extent of woody vegetation cover, and by being relatively accessible and wealthy. Data were collected through questionnaires with 316 participants in November and December 2021, applying stratified and convenience sampling in eight kebeles (two from each social-ecological archetype), and in one town. In particular, the questionnaire focused on 11 locally relevant ES and four value types (direct use, exchange, relational, intrinsic), and consisted of questions with regards to people's individual characteristics and their social-ecological context, a picture-based ES ranking exercise, and an exercise of distributing coffee beans to assess the types of values ascribed to each ES. To understand how rankings of ES relate to people's individual characteristics, their social-ecological context, and the types of values they ascribe to ES, I used descriptive statistics, hierarchical clustering, and chi-square tests of independence. First, I summarized the relative importance of ES and value types, and the values participants ascribed to individual ES with descriptive statistics. Second, participants were clustered (hierarchical clustering with Kendall distance) based on their picture-based ES ranking into beneficiary groups. Lastly, I assessed differences between these groups in their individual characteristics and their social-ecological context by applying a chi-square test of independence. Data and results of this chapter are partly integrated into Chapter V.

Chapter V: A social-ecological approach to support equitable land use decision making
Chapter V is both a conceptual and an empirical study, with a focus on decision making, and mainly addresses RA3 "To develop an approach to decision-making that integrates results of ES disaggregation". In this chapter, I presented a generalized, social-ecological approach to support equitable land use decision-making, and its application to the case study region. First, I presented a six-step approach to support land use decision-making, combining scenario planning with equity-focused, disaggregated analyses of ES provision and appropriation. Second, I applied this approach to 66 kebeles in the case study region (excluding state forest kebeles). To this end, I used data of Chapters III and IV, plus additional ecological and social data previously collected in the case study region, mostly as part of the SESyP and the ETH-Coffee projects (Duguma et al. Under Review in Communications Earth & Environment; Shumi et al. 2019; Jiren et al. 2020b; Beche et al. 2022; Duguma et al. 2022; Jiren et al. 2022; Zewdie et al. 2022; Duguma et al. 2023). Throughout the overall research process, diverse methods were employed: hierarchical clustering to derive the four social-ecological kebele archetypes, participatory scenario planning, satellite imagery and proximity-based InVEST scenario generation to create LULC maps, regression models to model potential per capita provision of 11 ES, as well as descriptive statistics to summarize data on the presence of different stakeholder groups with specific interests in local ES. In addition, ES specialization and values ascribed to ES were analyzed similarly to Chapters III and IV.

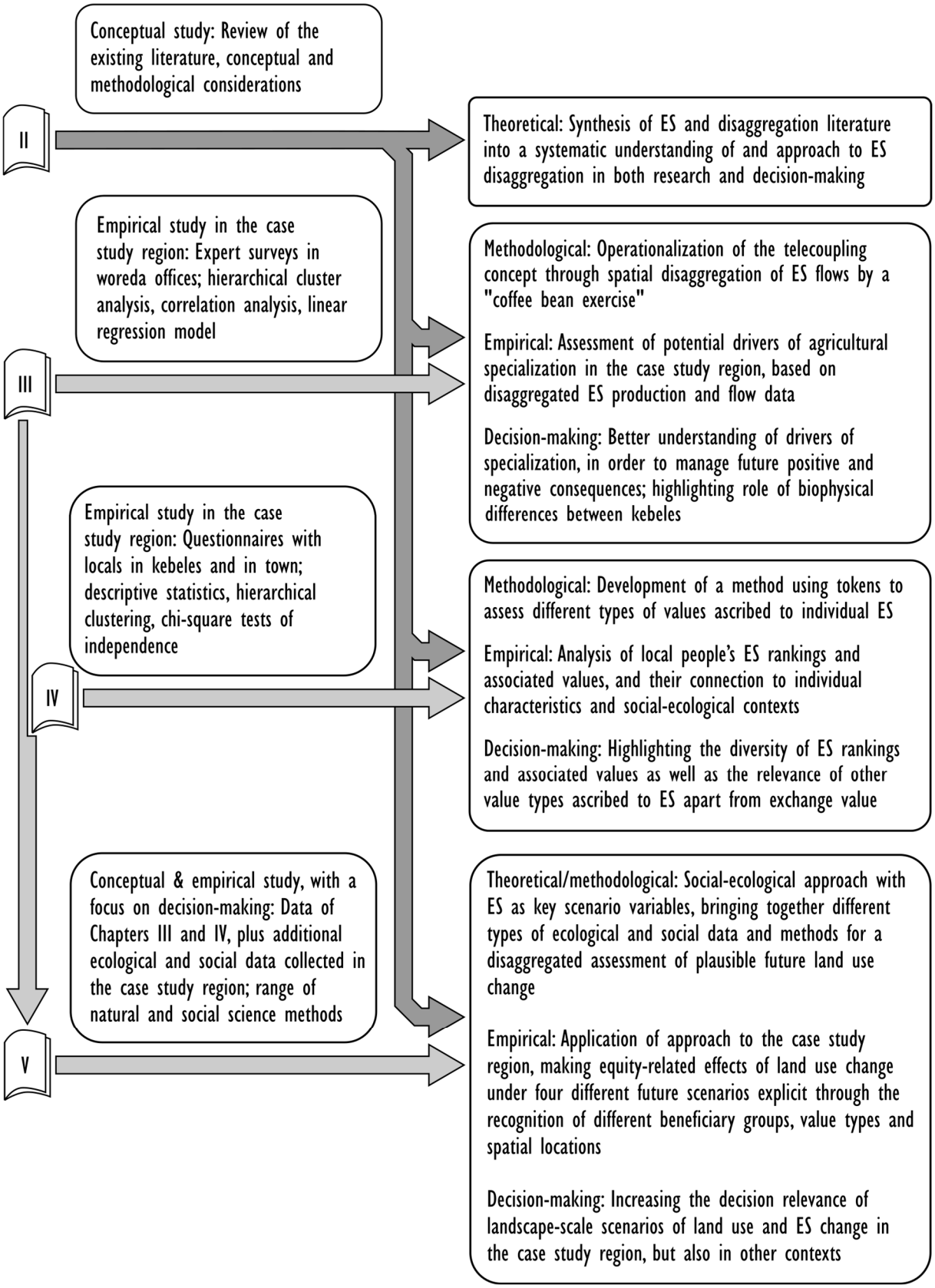

Figure 3. Methods (left-hand side boxes) and contributions (right-hand side boxes) of the individual chapters (II-V) of this dissertation. Chapter II is the conceptual basis and hence contributes to all other chapters. Data and results of Chapters III and IV are partly integrated into Chapter V. The chapters do not only make theoretical, methodological and empirical contributions to the ES literature, but also contributions to decision-making.

3. Key findings and contributions

This section summarizes the key findings of each chapter (II-V) as well as their theoretical, methodological, empirical and decision-making-related contributions (Figure 3).

Chapter II: Broadening the scope of ecosystem services research: Disaggregation as a powerful concept for sustainable natural resource management

Based on a literature review, I highlighted four equity issues that are obscured in aggregated ES assessments: (1) intragenerational equity in relation to power dynamics, (2) trade-offs between different values ascribed to ES, (3) intragenerational equity across space, and (4) intergenerational equity in relation to sustainable resource use. Similar to suggestions made by Mandle et al. (2020) and Bennett et al. (2015), I then proposed and discussed four disaggregation dimensions that can address these issues, and that are useful for assessing the equity implications of ES provision and appropriation, namely beneficiary groups, value types, space, and time. Based on this, I presented a generally applicable, structured approach to assessing ES in a disaggregated way, following four steps: (1) Identification of disaggregation context based on the equity issues that are most relevant in the case study context, (2) Selection of disaggregation dimensions and categories into which to disaggregate, (3) Selection of methods for analysis that match the case study context, (4) Synthesis and reflection of interactions, visualization, and necessary adjustments. Finally, I discussed in depth the role of disaggregated analyses in decision-making: integrating results of disaggregated ES analyses can help to alleviate different equity issues in ES governance, for example by designing polices that strengthen ES appropriation by disadvantaged groups. This chapter thus makes a theoretical contribution by synthesizing literature on ES and disaggregation into a systematic understanding of and approach to ES disaggregation in both research and decision-making.

Chapter III: Drivers of ecosystem service specialization in a smallholder agricultural landscape of the Global South: a case study in Ethiopia

Both telecoupling and comparative advantage were positively and significantly correlated with specialization, and the linear model showed that more telecoupled kebeles were more specialized in their ES production. According to the linear model, the positive relationship between comparative advantage and specialization grew stronger with altitude. Hierarchal clustering of ES production data resulted in three clusters of kebeles, representing three different farming types ("beef", "coffee/honey", "mixed"). These three kebele farming types differed in their altitude as well as in the correlations between specialization, telecoupling and comparative advantage.

This chapter makes methodological, empirical as well as decision-making-related contributions. In a data-scarce environment (official data on ES flows at fine spatial scales were not available), the telecoupling concept was operationalized through spatial disaggregation of ES flows, using a participatory "coffee bean exercise" as an alternative data collection method. Furthermore, I empirically assessed potential drivers of agricultural specialization in the case study region, based on disaggregated ES production and flow data. On the whole, the chapter produced results that can help decision-makers to better understand possible future landscape change and therefore make more informed decisions about ES management: there is a need to balance potential positive and negative consequences of specialization, and kebeles should not be managed uniformly, but decision-making should consider social-ecological differences between kebeles.

Chapter IV: Plural valuation in southwestern Ethiopia: Disaggregated ecosystem service values in a smallholder landscape

Clustering participants based on the ES ranking exercise resulted in five beneficiary groups, each of which prioritized a different set of ES (and was named accordingly): the cereal croppers, the cash croppers, the livestock owners, the forest users, and the diverse ES users. These beneficiary groups were associated with occupation (being a farmer or not), however, they were not associated with any other individual characteristics (gender, wealth). Each of the five beneficiary groups was strongly positively, and meaningfully, associated with one of the four social-ecological kebele

archetypes: for example, the livestock owners were strongly positively associated with the pasture-cropland kebele archetype, which was characterized by high availability of pasture. Moreover, beneficiaries generally prioritized those ES that were mostly produced by their group. Overall, direct use and relational value were judged more important than exchange and intrinsic value, and beneficiaries ascribed diverse and often multiple values to a given ES. Beneficiaries in the five groups ascribed different types of values to their prioritized ES: for example, forest users ranked honey and coffee comparatively high, and the exchange value of coffee and honey and the relational value of honey were more important to them than to beneficiaries in the other groups.

This chapter makes methodological, empirical as well as decision-making-related contributions. First, I developed my own participatory assessment method using coffee beans, inspired by approaches in the literature, in order to assess different types of values ascribed to a single ES. What is more, the chapter generated empirical insights into local people's assessments of ES and associated values, and how this connects to individual characteristics and social-ecological contexts. Based on the results, decision-making in the case study region should consider the diversity in assessments of ES and associated values, as well as other types of values ascribed to ES apart from exchange value.

Chapter V: A social-ecological approach to support equitable land use decision making
This chapter proposed six steps to generate and analyze scenarios of disaggregated, landscape-scale changes in land use and ES provision and appropriation: (1) Set system boundaries and units of analysis for spatial (dis-)aggregation, (2) Develop narrative scenarios, (3) Translate scenarios into spatially explicit LULC maps, (4) Analyze biophysical changes related to ES, (5) Analyze socioeconomic changes related to ES, and (6) Communicate results for decision-making. The application of the approach to the case study region recognized different beneficiary groups, value types and spatial locations: spatially explicit social-ecological kebele archetypes (which represented different beneficiary groups), different stakeholder groups in the development of scenario narratives, value types as key socioeconomic variables, and spatially explicit results with regard to LULC and ES changes. In this way, all steps of the proposed approach facilitated the consideration of distributional, recognitional, and procedural equity issues related to ES. This chapter not only highlighted winners and losers among the social-ecological archetypes in terms of biophysical and socioeconomic ES-related changes under the four future scenarios, but also incorporated recognitional and procedural equity through the participatory approach to scenario planning, the recognition of the different kebele archetypes with differing values and social-ecological contexts, and the analysis of the presence of different stakeholder groups.

Thus, this chapter makes theoretical, methodological, empirical as well as decision-making-related contributions. It provides a social-ecological approach that uses ES as key scenario variables, bringing together different types of ecological and social data and methods for a disaggregated assessment of plausible future land use change. Moreover, the application of the approach to the case study region made explicit equity-related effects of land use change under four different future scenarios. In this way, the decision relevance of landscape-scale scenarios of land use and ES change can be increased. For the case study region, the disaggregated results show that future strategy development by local smallholders and decision-makers needs to be context-specific, in order to appropriately mitigate and adapt to future changes. The general approach synthesized in this chapter could be applied to other contexts, especially in the Global South, where, similar to the case study region, people are often closely dependent on nature and especially vulnerable to change.

4. Synthesis

In contrast to aggregate ES assessments, in this dissertation, I propose to analyze ES along four disaggregation dimensions, in order to better assess and address equity issues. The overarching research question of this dissertation was to understand how this can be realized, responding to gaps in the ES literature with regard to theory and methodology, empirics, and decision implementation of ES disaggregation. Building on the conceptual insights of Chapter II, the three empirical chapters each address certain disaggregation dimensions (beneficiary groups, value types, space, time) and equity issues (distributional, recognitional, procedural; Figure 4). In this section, by bringing together the key findings and contributions of the individual chapters of this dissertation, I present four key insights into how analyzing ES in a disaggregated way can indeed help to better assess and address equity issues (Figure 4). These four key insights are:

Disaggregated analyses of ES help to better assess and address equity implications by:

(1) providing a useful lens to highlight equity issues connected to the ES delivery process
(2) encouraging the use of alternative methods and approaches to assess equity implications
(3) delivering equity-focused, place-based understandings of SES
(4) generating equity-related insights for decision-making

By putting disaggregation into focus, this dissertation as a whole makes theoretical, methodological and empirical contributions to the ES literature, but also contributions to decision-making around the governance of ES. In this section, I derive the four key insights, and discuss them in light of the literature (sections 4.1-4.4), before summarizing the overall contribution of this dissertation (section 4.5).

4.1 ES disaggregation provides a useful lens to highlight equity issues

This dissertation proposed four disaggregation dimensions and suggested that they highlight equity issues that remain hidden in aggregate ES assessments. Here, I relate the disaggregation dimensions to distributional, recognitional and procedural equity, three types of equity issues that are prominently discussed in the ES literature (Leach et al. 2018; Loos et al. 2022). Throughout this dissertation, different parts of the ES delivery process in the case study region (potential provision, flows/appropriation, values/benefits, governance) were empirically examined, using the four disaggregation dimensions as a lens to highlight equity issues (see Figure 5a-c).

By focusing on flows and appropriation of ES through the lens of spatial disaggregation, which took place at the kebele level, and along five spatial scales, I generated insights into spatial distributional differences of ES production between kebeles in the case study region, and partly into spatial distribution across distances (in terms of telecoupling; Chapter III; Figure 5a). Moreover, I highlighted differences between beneficiary groups in their ES rankings, their social-ecological context and the values they ascribe to ES (Chapter IV). This was achieved by analyzing values and benefits of ES through disaggregation by beneficiary groups and value types, which involved a post-hoc clustering of participants into groups with different ES rankings, and disaggregation of values into four types. An additional step was to explicitly interpret the social-ecological kebele archetypes in the case study region as spatially explicit beneficiary groups (hence: pre-determined groups as suggested in Chapter II). This helped to highlight distributional heterogeneity in space and between beneficiary groups in terms of potential provision, flows/appropriation and values/benefits (Chapter V).

Furthermore, through disaggregation of values and benefits of ES by beneficiary groups and value types, differences in ES rankings and values between five beneficiary groups were highlighted, and hence helped to recognize the diversity of people's priorities and values connected to ES (Chapter IV; Figure 5b). Interpreting the social-ecological kebele archetypes as spatially explicit beneficiary groups allowed to recognize the diversity among these groups in terms of potential provision, flows/appropriation and values/benefits (Chapter V). Extension of the analysis to four scenarios

added a time dimension – and this helped to recognize how distributions and preferences might change in the future (heterogeneity between beneficiary groups in ES provision, specialization and values; Chapter V). Finally, the analysis of governance aspects, in terms of the stakeholder groups present in the landscape, generated insights regarding procedural equity (Chapter V; Figure 5c).

Seeing that many ES assessments still rarely incorporate the socioeconomic or benefits side of the ES delivery process (Mandle et al. 2020), the focus in the assessments on flows/appropriation and values/benefits contributed new empirical examples to this gap. Whereas all four disaggregation dimensions served as a lens of analysis throughout the dissertation, the focus was on disaggregation by beneficiary groups, which occurs rarely in the literature (Mandle et al. 2020). In the ES literature in general, the focus has been on distributional equity (Leach et al. 2018; Loos et al. 2022), which is mirrored by the empirical assessments in this dissertation, where many insights were gained for distributional equity, some for recognitional equity, but only few for procedural equity (Figures 5a-c). Despite this drawback, the insights into recognitional equity gained through this dissertation can feed into governance and decision-making processes to improve procedural equity in the case study region (Leach et al. 2018), and other research in the case study region has already carved out governance-related implications with regard to ES (Jiren et al. 2022).

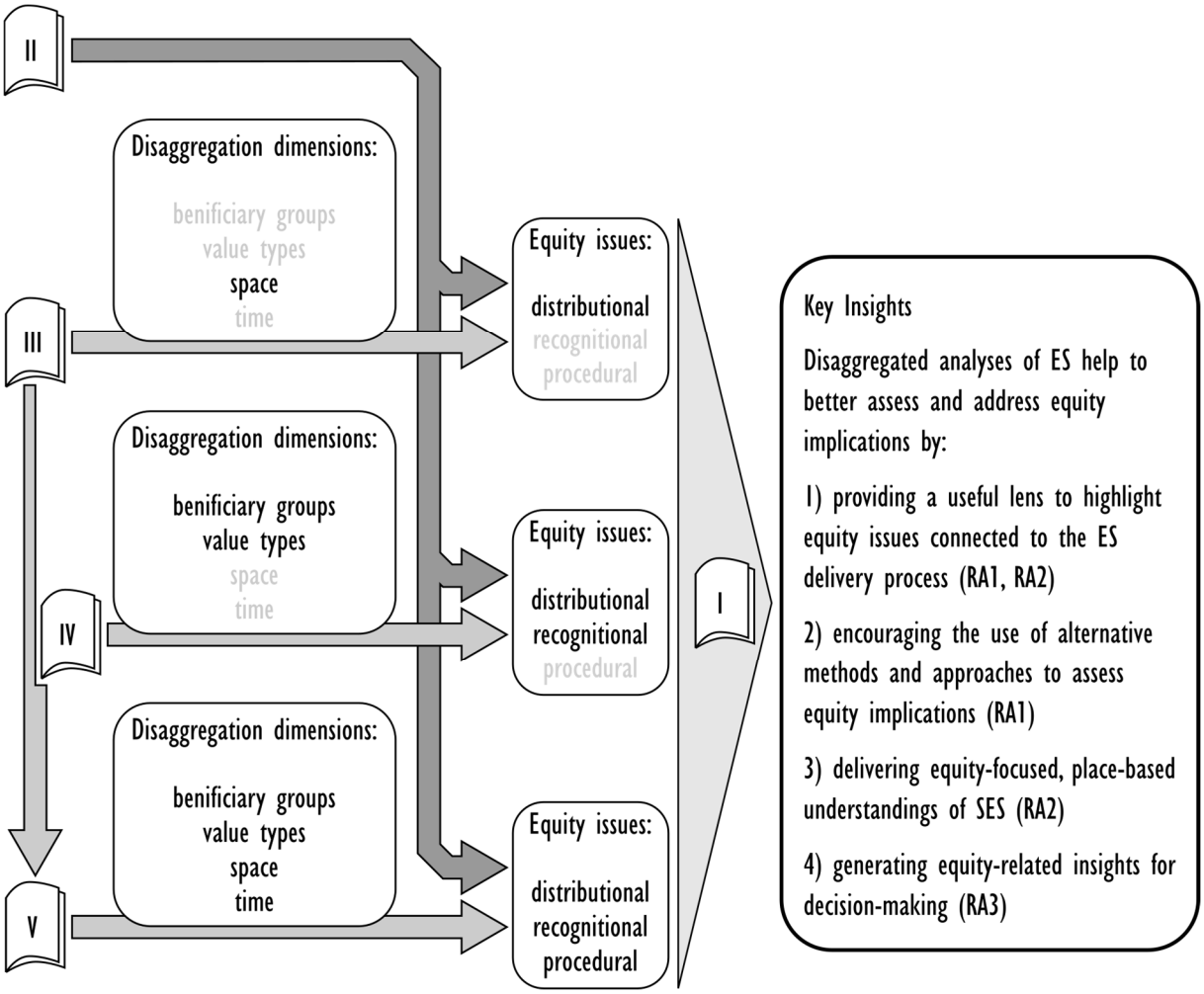

Figure 4. Synthesis of the four individual chapters into four key insights. Each of the three empirical chapters (III, IV, V) addresses certain disaggregation dimensions (beneficiary groups, value types, space, time) and equity issues (distributional, recognitional, procedural; see section 4.1). This framework chapter (Chapter I) synthesizes the results and contributions of the four individual chapters into four key insights into how ES disaggregation can indeed help to better assess and address equity issues. Each key insight relates back to one or two of the three research aims (RAs) of this dissertation (see section 4.5).

Regarding the relationships between the four disaggregation dimensions and the three equity issues, the empirical application in this dissertation confirms what is stated in the literature (section 1.1, Chapter II): disaggregation by beneficiary groups mainly assesses and addresses distributional equity issues, but can also reveal recognitional and procedural equity issues, whereas disaggregation by value types mostly relates to recognitional, but also partly to distributional equity. Additionally, disaggregation by space reveals distributional equity issues, whereas time disaggregation usually connects to (intergenerational) distributional equity, but might also provide room for recognition of potential future changes in who benefits from ES, and how. Understanding interdependencies between disaggregation dimensions is crucial (as discussed in Chapter II), and simultaneous consideration of multiple dimensions is necessary to derive in-depth insights with regard to multiple equity issues (as exemplified in Chapter V). All things considered, disaggregation along the four dimensions beneficiary groups, value types, space and time provided a useful lens of analysis to highlight different equity issues connected to the provision and appropriation of ES in the case study region.

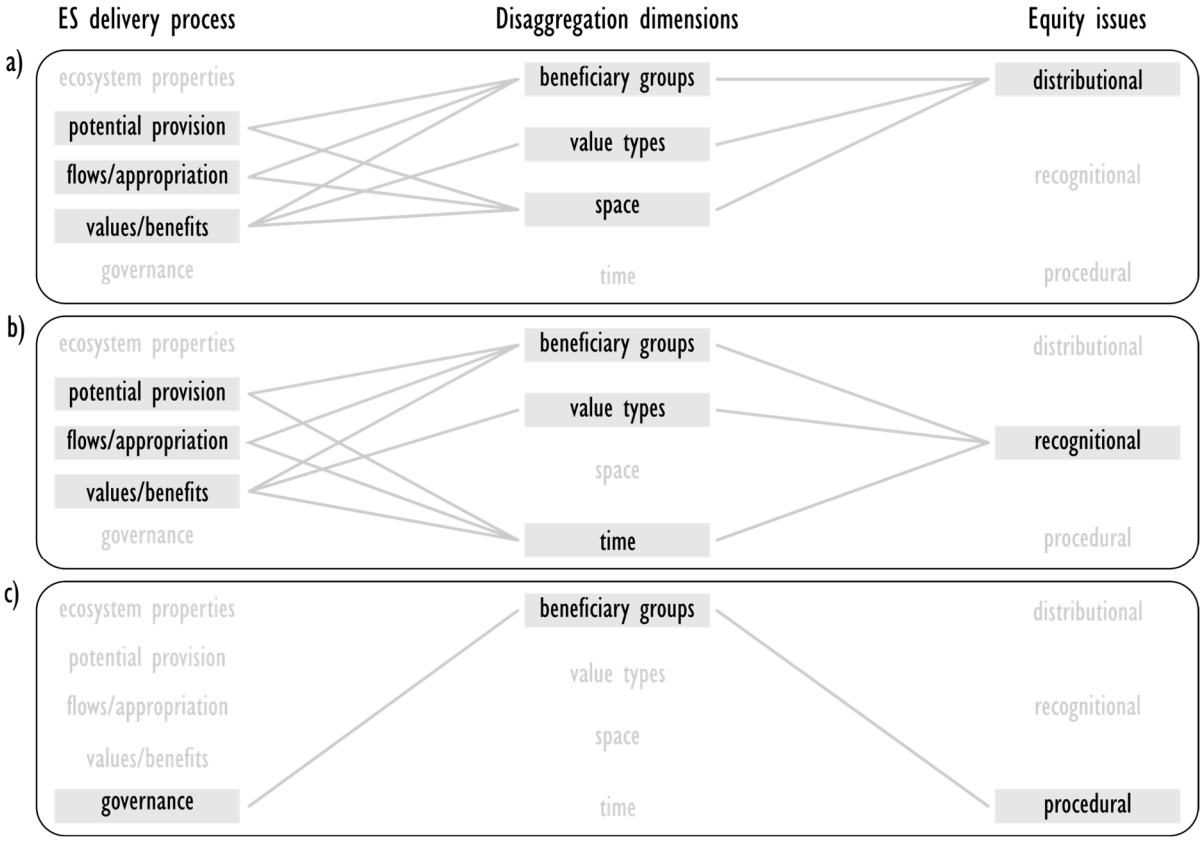

Figure 5. The relationships between steps of the ES delivery process, disaggregation dimensions and equity issues. The ES delivery process in the case study region was empirically examined along four disaggregation dimensions (beneficiary groups, value types, space, time), consequently highlighting (a) distributional, (b) recognitional, and (c) procedural equity issues (see section 4.1).

4.2 ES disaggregation encourages the use of alternative methods

SES research in general promotes conceptual and methodological pluralism, because research questions are usually complex and inspired by real-world problems (Fischer et al. 2015; Vos et al. 2019; Biggs et al. 2021). Likewise, the ES analyses in this dissertation, which were undertaken under a place-based SES approach, relied on alternative methods and approaches to obtain and analyze disaggregated data, which in turn proved useful in highlighting equity implications. Here, I discuss three of them: selecting ES based on local relevance and not according to pre-defined categories, using coffee bean exercises as a participatory means to obtain disaggregated data, and using cluster analysis as an approach to reduce complexity.

Traditional ES assessments often select their focal ES by balancing the four categories of provisioning, cultural, regulating and supporting ES (Millennium Ecosystem Assessment 2005; MA). However, to select the ES analyzed in this dissertation, I did not follow such a traditional approach, but selected a set of ES, which were, based on previous research in the case study region, relevant to local people (Manlosa et al. 2019a; Manlosa et al. 2019c; Shumi et al. 2019; Duguma et al. 2023). Although there was a number of ES that re-occurred in each of the empirical chapters, the exact ES chosen differed between chapters due to considerations of practicality (e.g. no official production data was available for firewood, khat or biodiversity; perceived values were not elicited for plantation coffee, since it is currently not present in the landscape). Despite the fact that the focus was mainly on provisioning ES (following the MA categorization), ES selection based on local relevance was still suitable to reveal differences along the different disaggregation dimensions, and ultimately highlight equity issues (see other key insights). Thus, instead of describing ES in a purely physical way, or in terms of pre-determined categories or types, they can alternatively be understood as complex social-ecological phenomena, with multiple benefits obtained from a single ES (Chan et al. 2012; Huntsinger and Oviedo 2014; Díaz et al. 2018; Chapter II).

Using coffee beans, or other types of locally familiar tokens, for data collection is a method that has, for example, been used for the participatory assessment of ES importance (Hicks et al. 2015; Lau et al. 2018). Drawing on this idea, I developed new, specific methods that were suitable to obtain the kind of disaggregated data needed from experts and locals in the case study region. Coffee beans were used as a means to elicit knowledge from experts, and to obtain assessments from local participants (section 2.4, Chapters III and IV). The results of these participatory "exercises" were then combined and analyzed together with other types of data (official government data, results of a picture-based ranking exercise), and finally, for example, helped to highlight the heterogeneity in spatial distributions of ES within the case study region and in connection to other parts of the world (Chapter III), to recognize the diversity of ES rankings and connected values (Chapter IV), or to even conduct a comprehensive assessment of biophysical and socioeconomic equity implications across four scenarios (Chapter V). Hence, this dissertation used alternative methods for data collection, which were adapted to the local context, and without which the generation of disaggregated results would not have been possible.

Results of disaggregated analyses are often complex and multidimensional, and thus they need to be communicated carefully, weighing completeness against communicability (Böttinger et al. 2020; Metze 2020; Chapter II). In this dissertation, I used clustering as an approach to reduce complexity, in order to re-aggregate results to a more accessible level (Sietz et al. 2019; Rocha et al. 2020; Pacheco-Romero et al. 2021). In particular, the four social-ecological kebele archetypes acted as a pre-determined organizing principle throughout this dissertation: they helped to select kebeles for which or in which to collect data (Chapters III and IV), to analyze the role of the social-ecological context (Chapter IV), and, finally, they represented four spatially explicit beneficiary groups for which equity implications were analyzed (Chapter V). In other instances, I relied on post-hoc clustering analyses to derive kebele farming types, or beneficiary groups based on ES rankings (Chapters III and IV). Such re-aggregation of disaggregated results is important for their successful communication and integration into further research and decision-making, in order to better address equity issues.

4.3 ES disaggregation delivers equity-focused understandings of SES

The disaggregated analyses of ES conducted in this dissertation allowed equity-related insights into the SES of the case study region. Here, two dominant overarching topics were the role of the social-ecological context for people's relationships with ES, as well as the development of the case study region towards specialization, intensification and market integration.

With regard to the social-ecological context, the disaggregated analyses showed its significant role in determining the relationship of people in the case study region with ES. Generally, different beneficiary groups, as represented by the social-ecological kebele archetypes, differed in their

biophysical and socioeconomic outcomes connected to ES, today and in the future (Chapter V). More specifically, people's social-ecological context (in terms of their kebele, and the ES they produced) was also connected to the way they ranked ES (Chapter IV). For example, forest users prioritized coffee and honey and were strongly associated with those kebeles that had a lot of woody vegetation. As a biophysical factor, mean altitude of a kebele played a significant role in determining the types of ES that were produced in it (see kebele farming types, Chapter III), but it also had a significant influence on the degree of ES specialization, as well as on the relationship between comparative advantage and specialization. The fact that the social-ecological context plays a significant role in determining people's relationship with ES has also previously been observed in the case study region itself, and elsewhere (Oteros-Rozas et al. 2014; Dorresteijn et al. 2017; Quintas-Soriano et al. 2018; Reyes-Arroyo et al. 2021; Schultner et al. 2021). The important role of the social-ecological context highlights distributional heterogeneity in how people use, connect to and benefit from ES, but also helps to recognize beneficiary groups and their differences, especially in decision-making.

This dissertation also allowed to better understand the progress towards and the implications of a potential development of the case study region towards specialization, intensification, and market integration. Specialization and market integration of the case study region, which come with opportunities but also many challenges, are strongly encouraged by the government, and many stakeholders expect or favor such developments (Federal Democratic Republic of Ethiopia, National Planning Commission 2016; Jiren et al. 2020a; Jiren et al. 2020b). Notably, over the past decades, production in the case study region has already started to shift from subsistence to marketed crops, and access to cash crops with indirect benefits increased (Schultner et al. 2021). With regards to the value changes associated with a development towards specialization, intensification, and market integration, it has been debated whether the modern market system can allow for the expression of relational values, or whether market systems are solely driven by instrumental value (Jones and Tobin 2018). For example, it has been shown that landscape simplification in agricultural landscapes negatively influenced particular relational values (Riechers et al. 2021). The results of this dissertation showed that, at present, both telecoupling (which can be interpreted as a proxy for market integration) and (to a lesser degree) comparative advantage drive ES specialization in the case study region, but also that the degree of both specialization and telecoupling in the case study region were still comparatively low (Chapter III). Moreover, exchange value was generally ranked lower than direct use and relational values, and reflected the general importance of ES in people's lives relatively poorly (Chapter IV). In the future, the outcomes with regard to specialization and values depend on which plausible future trajectory the case study region will follow (Chapter V). For example, for the two intensified land use scenarios, specialization will increase, whereas it will decrease under the two integrated land use scenarios. Generally, for specialization, telecoupling and values, there is heterogeneity across beneficiary groups at present (see insights with regard to distributional equity in section 4.1), but also in the future, both with regard to the intensity of these developments, and with regard to resilience across the scenarios (Chapter V). As can be seen, despite being favored by many stakeholders, the case study region has not progressed yet very far along the trajectory towards specialization, intensification, and market integration. Nonetheless, it is a probable development of the landscape that comes with important implications in terms of how people benefit from ES, and that will likely not play out in the same (beneficial or detrimental) way for everyone in the landscape. These results thus highlighted the heterogeneity across the case study region in terms of (potential) developments connected to specialization, today and in the future, and the importance of recognizing and planning for these differentiated developments in decision-making.

Derived from a place-based SES and disaggregated approach, the results regarding the role of the social-ecological context and the development towards specialization are specific to the SES of the case study region. Indeed, the place-specific results extend and complement previous equity-related insights into the case study region (e.g. with regard to smallholder heterogeneity, or governance

preferences of different stakeholder groups; see section 2.3). With this, they follow in the footsteps of other place-based SES research, which has helped to deepen SES science, through, for example, shedding light on local transformational change, revealing the social dynamics shaping SES, or bringing together diverse types of knowledge (Balvanera et al. 2017; Norström et al. 2022). The challenge of the transferability of the results, common to results of place-based approaches, can be addressed, for example through the establishment of long-term research networks and global practice communities (Balvanera et al. 2017; Martín-López et al. 2020; Norström et al. 2022).

4.4 ES disaggregation generates equity-related insights for decision-making

The disaggregated analyses conducted in this dissertation generated equity-related insights that are relevant for decision-making in the case study region. A better understanding of the drivers of ES specialization, and their heterogeneity across the landscape, can help to proactively manage its positive and negative consequences (Chapter III). Moreover, recognizing the importance of value types other than exchange value to local people, and the diversity of people's ES and value rankings, which connect to their social-ecological context, can make decision-making with regard to future changes in the landscape more equitable and sustainable (Chapter IV). The same holds true for knowledge about future biophysical and socioeconomic ES-related outcomes, and equity-related effects of land use and ES change (Chapter V). Generally speaking, to enhance equitable decision-making in the case study region it is recommendable to apply context-specific (and not uniform) management of kebeles, to recognize heterogeneity in people's relationship with ES across space and between beneficiary groups, and to pay attention to the role of the social-ecological context, especially when it comes to planning for the management of future developments.

Even so, implementation of such insights in the case study region is challenging due to hierarchical governance structures and limited agency of smallholder farmers (Jiren et al. 2018a; Shumi et al. 2019; Jiren et al. 2022; Manlosa 2022). However, one of the principles of a widely shared, common vision for the future of the landscape, which was developed by local farmers and decision-makers, is "collaborative governance and institutions" (Jiren et al. 2023a). This includes decentralized governance, participatory landscape management, as well as equitable sharing of benefits from trade and natural resources. If the results of this visioning process are translated into tangible steps, including more collaborative governance, the insights of this dissertation can be used to inform more decentralized, participatory and context-specific ES governance in the case study region.

4.5 Summary: ES disaggregation helps to better address equity and sustainability

This dissertation set out to understand how disaggregated analyses of ES can help to better assess and address equity implications of ES provision and appropriation, in order to align the ES concept with sustainability. To address the gap of a missing systematic approach to ES disaggregation, I explored new theoretical and methodological approaches to ES disaggregation (RA1). Chapter II in itself made a foundational theoretical contribution here, by defining what disaggregation means, introducing and discussing the four disaggregation dimensions that are central to this dissertation, and providing ideas for a systematic approach to disaggregation. Moreover, synthesizing across the chapters of this dissertation, I showed that the four disaggregation dimensions can indeed act as a useful lens to highlight distributional, recognitional, and procedural equity issues connected to ES delivery (key insight 1), and that disaggregated analyses encourage the use of alternative methods and approaches that are useful for highlighting equity implications (key insight 2).

Empirical, disaggregated ES assessments remain scarce in the ES literature, and hence, this dissertation aimed to empirically examine ES disaggregation along different dimensions in an Ethiopian case study region (RA2). Across the three empirical chapters, I highlighted equity issues by using the four disaggregation dimensions as a lens to the ES delivery process (key insight 1). Through this process, I was able to generate equity-focused, place-based understandings of the SES of the case study region (key insight 3), with regard to the role of the social-ecological context, and the development of the case study region towards specialization and market integration.

To address the gap of lacking integration of ES research results into decision-making, I set out to develop an approach to decision-making that integrates results of ES disaggregation (RA3). Here, Chapter V presents a generalized, social-ecological approach to support land use decision-making, and thus addresses this aim directly. What is more, through the application of ES disaggregation across the chapters of this dissertation, I was able to generate equity-related insights for decision-making in the case study region (key insight 4).

In this dissertation, I have thus highlighted the various ways in which disaggregation can help to better assess and address equity implications connected to ES. Considering that achieving inter- and intragenerational equity within ecological limits is the core goal of sustainability (World Commission on Environment and Development 1987; Schröter et al. 2017), making equity more prominent in ES research and decision-making through disaggregation ultimately connects to and promotes sustainability. From a SES perspective, sustainability and equity dynamically interact, and results of this dissertation can, for example, support policies that promote access to ES for disadvantaged groups, or ensure that people's diverse ES priorities are recognized in decision-making, and, in this way, promote equity and sustainability at the same time (Leach et al. 2018; Zafra-Calvo et al. 2020; Pascual et al. 2023). The contributions of this dissertation hence ultimately help to align ES research and decision-making with equity, as well as with sustainability as an overarching normative goal.

5. Outlook

Following calls for necessary improvements in response to remaining gaps in ES research, especially regarding the integration of equity issues in ES assessments (Bennett et al. 2015; Bennett 2017; Kadykalo et al. 2019; Mandle et al. 2020; Loos et al. 2022), this dissertation put forward disaggregation as a tool to better assess and address equity issues in ES research and decision-making. In contrast to traditional, aggregated ES assessments, which essentially look at how much of a given service is provided in total, or refer to the combined value of those services (Daw et al. 2011), this dissertation highlighted how ES disaggregation can support the analysis of equity implications. Despite its contributions, the results and insights derived in this dissertation leave room for future research.

First, this dissertation made a strong theoretical contribution, by defining what disaggregation means, introducing four disaggregation dimensions, providing ideas for a systematic approach to disaggregation, and showing that the four disaggregation dimensions can indeed act as a useful lens to highlight equity issues. Nonetheless, an encompassing, systematic review of disaggregated studies would be an additional useful contribution, independent of whether studies are based on the ES or NCP concept. Such a review would allow to derive current foci and gaps in terms of the steps of the ES delivery process, the disaggregation dimensions and the equity issues addressed, to guide future research. Equally important, it would also allow for an overview and potential integration of existing disaggregated, place-based research results so far.

Second, this dissertation revealed that disaggregated analyses encourage the use of alternative methods and approaches that are useful for highlighting equity implications. The approaches employed in this dissertation, such as the use of tokens to elicit disaggregated data, could be transferred and tested in other case study regions, particularly in the Global South. Especially the assessment of plural values is of interest here, for example trying to understand how values can be quantitatively studied without introducing biases, or how potential future changes in value ascription can be assessed.

Third, this dissertation conducted disaggregated empirical ES assessments in the case study region, showing how the four disaggregation dimensions can act as a lens to highlight equity issues, and generating equity-focused, place-based understandings of the local SES. The focus here was on ES

of local relevance, which hence highlighted mostly local equity issues, but an extension to globally relevant ES as well as global beneficiaries could add insights with regard to the global scale. Throughout the empirical assessments in this dissertation, ecosystem properties, the time dimension and procedural equity issues stayed on the sideline. Whereas governance and power related issues have already been studied in the case study region (Jiren et al. 2018a; Jiren et al. 2020a; Jiren et al. 2022), and thus addressed procedural equity, future studies in the case study region could put their focus on better understanding inter-generational equity issues in terms of (un)sustainable ES flows, i.e. to what extent certain forms of ES appropriation entail the liquidation of natural capital stocks. Additionally, monitoring the development of the case study region into the future, e.g. in terms of ES specialization and values, would be interesting to contrast and compare with the four scenarios and the future vision which were developed for the landscape.

Finally, this dissertation presented a generalized, social-ecological approach to support land use decision-making, and generated equity-related insights for decision-making in the case study region. Correspondingly, future studies could look into how these results can be best communicated to local people and decision-makers, in order to ensure their uptake in decision-making. This goes hand in hand with a monitoring of the development towards more collaborative governance, as envisioned, which would ultimately facilitate the integration of results into decision-making.

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Chapter II: Broadening the scope of ecosystem services research: Disaggregation as a powerful concept for sustainable natural resource management

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Broadening the scope of ecosystem services research: Disaggregation as a powerful concept for sustainable natural resource management

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ABSTRACT

Most assessments of ecosystem services to date are aggregate assessments. Despite their usefulness as a first approximation of how nature is valuable to people, they can obscure important inter- and intragenerational equity issues, which are vital in a policy context, particularly with regard to sustainability. In this conceptual paper, we aim to strengthen the position of disaggregation in ecosystem services research and policy making. Based on existing literature, we highlight four equity issues that remain hidden in aggregate ecosystem service assessments. We then suggest and discuss four disaggregation dimensions (beneficiary groups, value types, space, and time) that can address these issues and are directly useful for assessing the equity implications of ecosystem service appropriation. Building on our conceptual and methodological considerations, we present a generally applicable, structured approach to assessing ecosystem services in a disaggregated way. Finally, we look more closely at the role of disaggregated analyses in policy making, where they provide crucial information necessary to understand the implications of changing natural resource management and ecosystem services appropriation, and argue that our multi-dimensional approach to disaggregation may result in alternative understandings of ecosystem services as complex social-ecological phenomena.

1. Introduction

Who gains from humanity's interactions with nature and in which ways? Irrespective of whether such gains are referred to as nature's contributions to people (Díaz et al., 2018; Díaz et al., 2015) or ecosystem services (Millennium Ecosystem Assessment, 2005), they will depend on the types of beneficiaries involved (across both space and time) and the values ascribed to nature. In this paper, we suggest that the disaggregated assessment of ecosystem services by beneficiary groups, value types, space and time will provide an improved basis for sustainability-related ecosystem services research and governance.

Our starting premise is that the ecosystem services concept is fundamentally linked to ideas of sustainability (Abson et al., 2014; Schröter et al., 2017). The ecosystem services concept has moved rapidly from a metaphor about humanity's dependence on the environment ("rivet poppers", Ehrlich and Ehrlich, 1981; Daily, 1997; Ehrlich and Mooney, 1983) to a dominant discourse in sustainability science (Costanza et al., 2017; Millennium Ecosystem Assessment, 2005). Most recently, acknowledging the limitations imposed by viewing such human-nature interactions in terms of services, the concept has been further refined as "nature's contributions to people" within the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Díaz et al., 2018). For the sake of brevity and consistency, in this paper, we refer to the benefits received by humans from their interactions with ecological structures and functions as "ecosystem services".

The ecosystem services concept provides a clear framework for linking ecological 'health' to human well-being (Haines-Young and Potschin, 2010), and can integrate numerous perspectives on sustainability (Abson et al., 2014). Following Schröter et al. (2017), we define sustainability as a state that meets the needs of current and future human generations within ecological limits (see also World Commission on Environment and Development, 1987). Sustainability is thus interlinked and interacts with (intra- and intergenerational) equity (Leach et al., 2018). In a decision making context, the ecosystem services concept has provided powerful arguments regarding the importance of nature to human well-being (Chaplin-Kramer et al., 2019; Díaz et al., 2019), thereby laying the foundation for influential governance tools

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such as payments for ecosystem services (Daily and Matson, 2008; Gómez-Baggethun et al., 2010).

Notwithstanding the rapid development of the field of ecosystem services, some key challenges remain (Bennett et al., 2015; Carpenter et al., 2009; Rieb et al., 2017). These include a failure to recognize pluralistic understandings of human-environment relations (Díaz et al., 2018; Norgaard, 2010), as well as explicit consideration of intra- and intergenerational equity issues related to the use of natural resources (Bennett et al., 2015; Mandle et al., 2020; Schröter et al., 2017). Most assessments of ecosystem services to date are aggregate assessments (Blythe et al., 2019; Cruz-Garcia et al., 2017; Suich et al., 2015). This means that they essentially look at how much of a given service is provided in total (Abson et al., 2010), or they refer to the combined value of those services (Costanza et al., 1997; Costanza et al., 2014). In effect, ecosystem services research is strongly oriented to identifying aggregate 'socially optimal' outcomes. However, such analyses overlook equity issues, which are vital in a policy context, particularly with regard to sustainability (Daw et al., 2011). Similarly, this aggregate approach creates a potential blind spot regarding which societal groups have, or do not have the power to appropriate beneficial ecosystem services (Berbés-Blázquez et al., 2016).

We define the disaggregated analysis of ecosystem services as an assessment of ecosystem services by a particular theme – such as who benefits, from which particular values, where and when. More specifically, we conceptualize ecosystem services disaggregation as the process of understanding the multiple, interdependent dimensions across which the various benefits of ecosystem services are appropriated and distributed. The dominant approach to disaggregation in the literature has been based on how to differentiate between types of ecosystem services (e.g. provisioning or cultural, Millennium Ecosystem Assessment, 2005), or intermediate and final services (Fisher et al., 2009) that may arise from different ecosystems (e.g. forests, agricultural land, oceans etc.). While this more biophysical aspect of disaggregation is vital, there is still a need to disaggregate the way in which different people appropriate and benefit from the specific ecosystem services arising from specific ecosystems. This 'social' disaggregation is the focus of this paper.

In this conceptual paper, we provide a systematic approach to disaggregation in ecosystem services research that is oriented towards sustainable natural resource management, and will ultimately help to better assess the equity implications of ecosystem service appropriation. Based on existing literature, we highlight four inter- and intragenerational equity issues that remain hidden in aggregate ecosystem service assessments: (1) intragenerational equity in relation to power dynamics, (2) trade-offs between different values ascribed to ecosystem services, (3) intragenerational equity across space, and (4) intergenerational equity in relation to sustainable resource use. These four issues reflect distributional, recognitional and procedural equity, with a main focus on distributional equity. We then present four dimensions of disaggregation that can address these issues, namely beneficiary groups, value types, space, and time. We highlight conceptual issues with, and methodological approaches to, disaggregation across each of the four dimensions, and present a stepwise approach to disaggregated assessments of ecosystem services. Finally, we look more closely at the role of such assessments in policy making, and discuss an alternative understanding of ecosystem services and their classification.

2. Ecosystem service assessments and equity

Aggregate assessments of ecosystem services, following the definition by Daw et al. (2011), are those that do not explicitly recognize distributional patterns among beneficiary groups, value types, locations or different points in time. Such aggregate assessments are useful, because they emphasize the overall importance of ecosystem services to decision makers (Abson et al., 2010; Costanza et al., 2014; Costanza et al., 1997). Notwithstanding these advantages, aggregate assessments potentially over-simplify the relationship between ecosystem services and human well-being (Daw et al., 2011). Changes in ecosystem services appropriation and trade-offs among services can create winners and losers, even if aggregate well-being derived from the ecosystem services increases (Carpenter et al., 2009; Cord et al., 2017; Rodriguez et al., 2006).

Equity issues may be "hidden" in aggregate assessments. This does not only entail inter- and intragenerational equity issues, but also potential trade-offs between different types of values associated with ecosystem services. Based on existing literature, we highlight four major equity issues that can be addressed by disaggregated analyses of ecosystem services: (1) intragenerational equity in relation to power dynamics, (2) trade-offs between different values ascribed to ecosystem services, (3) intragenerational equity across space, and (4) intergenerational equity in relation to sustainable resource use (Table 1).

First, power dynamics as well as demographic and socioeconomic factors influence people's access ("the ability to derive benefits from things", Ribot and Peluso, 2003, p. 153) to ecosystem services. This, in turn, determines to what extent people can benefit from nature (Fisher et al., 2014; Horcea-Milcu et al., 2016). For example, richer households in southern Ethiopia were better able to take advantage (semi-legally or illegally) of ecosystem services from reforestation areas, although they were less dependent on those services than poorer households (Byg et al., 2017). How ecosystem services contribute to people's well-being thus depends on their individual demographic and socioeconomic contexts (Daw et al., 2016; Dawson and Martin, 2015), and policies based on aggregate assessments of ecosystem services could inadvertently further marginalize already disadvantaged groups (Daw et al., 2015).

Second, values and priorities that people ascribe to ecosystem services are diverse (Lau et al., 2019; Pascual et al., 2017). For example, values held by fishers and farmers for wetland ecosystem services in Shaoguan (China) differed substantially from the values that were predicted by monetary valuation, whereas values held by business owners and government officials were positively correlated with modelled monetary values (Brooks et al., 2014). The types of benefits from ecosystem services are also diverse: people may benefit directly from ecosystem services (reflects direct use value), but also indirectly through cash income (reflects exchange value) or employment. This suggests that it is important to distinguish different types of values, and preferences for those values, to understand distributional issues within society (Daw et al., 2011).

Third, geographical location can influence people's access to ecosystem services (Dorresteijn et al., 2017; Serna-Chavez et al., 2014). For example, the well-being of rural people in Rwanda living adjacent to native tropical forest was influenced by access to suitable substitutes of forest ecosystem services occurring in the surrounding landscape (Dawson and Martin, 2015). Furthermore, it is crucial to consider multiple spatial scales when analyzing ecosystem services, because such services are generated and appropriated at various scales (Hein et al., 2006). Ecosystem service flows do not necessarily align with impacts (Kleemann et al., 2020), and aggregate assessments rarely recognize inter-regional ecosystem service flows – a key shortcoming with respect to issues of environmental justice in a telecoupled world (Kleemann et al., 2020; Liu et al., 2013; Martín-López et al., 2019).

Fourth, ecosystem service flows may deplete natural capital and thus be unsustainable over time (Villamagna et al., 2013). Following Barbier (2019), we define natural capital here as an endowment of natural resources (including land, forests, fossil fuels, minerals, fisheries, and all other natural resources), including goods and services provided by ecosystems. For example, balances between capacity and flow for moose hunting in Telemark County (Norway) were negative (harvesting rates larger than recruitment rates), whereas balances for sheep grazing were positive (Schröter et al., 2014). Moreover, ecosystem service supply or preferences may change over time (Rau et al., 2018). However, such temporal changes are rarely included in assessments to date (Abson et al., 2010; Hein et al., 2016b), and assessments that aggregate across

Table 1
Examples of four equity issues that are relevant to ecosystem service assessments.

Equity issue	Examples
Intragenerational equity in relation to power dynamics	• In a community forestry in Nepal, wealthier households had better access to ecosystem service benefits than less wealthy groups, despite social equity provisions built into institutional structures (Chaudhary et al., 2018). • Stakeholders from formal institutions (government bodies, scientists, schools, universities) in north-eastern Spain held strong power in controlling the access of other groups through the management of keystone supporting ecosystem properties and intermediate regulating services (Felipe-Lucia et al., 2015). • In central Romania, a key contextual factor mediating the relationship between farming ecosystem services and well-being of potential beneficiaries was household decisions and individual contexts (Horcea-Milcu et al., 2016).
Trade-offs between values ascribed to ecosystem services	• Local people referred most frequently to relational values of Otún River watershed in Colombia, whereas intrinsic and instrumental values were mentioned less frequently. Rural respondents mentioned relational and intrinsic values more often than urban respondents (Arias-Arévalo et al., 2017). • Rural households in southwestern Ethiopia have recently gained better access to cash crops such as khat (*Catha edulis*), eucalyptus (*Eucalyptus spp.*) and coffee (*Coffea arabica*). However, such cash-generating ecosystem services may crowd out other crops that deliver more direct benefits to subsistence farmers (Schultner et al., 2021).
Intragenerational equity across space	• The ability of First Nations communities on coastal Vancouver Island (Canada) to realize benefits from shellfish harvesting was limited (among others) by geographical location (Wieland et al., 2016). • Ivory Coast and Ghana supplied more than half of Germany's cocoa, but the main negative impacts of Germany's cocoa consumption for biodiversity occurred in Cameroon and Ecuador. Ecosystem service flows thus do not necessarily align with impacts (Kleemann et al., 2020).
Intergenerational equity in relation to sustainable resource use	• Flows of ecosystem services from Hoge Veluwe national park (Netherlands) and the associated values have varied over time, with major shifts within decades and less: the importance of wood harvesting declined steadily during the 1970 s and 1980 s, whereas recreation gradually became more important after the Second World War (Hein et al., 2016b). • After an adjustment of the management strategy of Chatthin Wildlife Sanctuary in central Myanmar locals were significantly more likely to like the sanctuary and more likely to mention benefits, whereas they were less likely to mention problems (Allendorf et al., 2017).

time are unable to distinguish whether ecosystem service flows are sustainable.

There are three types of equity that are often discussed in the literature: distributional, recognitional and procedural equity (Fraser, 2009; Leach et al., 2018; Schlosberg, 2007). Distributional equity has been the main focus in equity and justice scholarship in the past decades and refers to the allocation of resources, costs and benefits among different people or groups. Procedural equity is concerned with the fairness of the political process that determines this allocation. Recognitional equity regards the consideration of and respect for different values, identities, rights and preferences of different social groups. These equity types have for example been discussed in contexts of payments for ecosystem services and urban ecosystem services (Langemeyer and Connolly, 2020; McDermott et al., 2013).

The four equity issues we highlight can be linked to all three types of equity. However, we focus more on the distributional (all four equity issues) and recognitional (intragenerational equity in relation to power dynamics, trade-offs between different values ascribed to ecosystem services) equity types. For example, trade-offs between different values ascribed to ecosystem services reflect distributional equity (as values determine the types of benefits derived from ecosystem services), but also recognitional equity (value pluralism highlights preferences of different social groups, Langemeyer and Connolly, 2020). Nevertheless, a better understanding of distributional and recognitional equity issues is likely to be key to developing governance of ecosystems services that seek to increase procedural equity (which is reflected in our discussion of power issues).

3. Introducing four dimensions of disaggregation

3.1. A shift towards disaggregation

As the ecosystem service concept is shifting from a metaphor to a decision making tool, the need to refine ecosystem service assessments becomes ever more pressing (Grêt-Regamey et al., 2017). For example, disaggregation across beneficiaries is a key factor for enabling ecosystem services research to effectively inform decisions (Mandle et al., 2020). A key challenge in policy making is to understand who benefits from ecosystem services, and how costs and benefits are distributed among different beneficiary groups at different spatial–temporal scales (Bennett et al., 2015; Rieb et al., 2017). Aggregate assessments of ecosystem services, as discussed in section 2, are limited in this context because they provide little information on the intra- and intergenerational distribution of ecosystem services (Schröter et al., 2017).

Instead, we suggest that ecosystem services research should shift more towards disaggregated analyses. Specifically, we suggest four dimensions of disaggregation, namely disaggregation by beneficiary groups, value types, space, and time. Such disaggregated assessments will highlight issues of intra- and intergenerational equity (see section 2) and thus help to make policy making regarding natural resource use and management more sustainable (see Bennett et al., 2015; Daw et al., 2011; Mandle et al., 2020; Rieb et al., 2017).

Many case studies on ecosystem services continue to overlook the need to disaggregate (Blythe et al., 2019; Cruz-Garcia et al., 2017; Suich et al., 2015). A recent structured review by Mandle et al. (2020) found that 31% of ecosystem service assessments disaggregated spatially, but only few assessments (7%) disaggregated by beneficiary groups. Mediating factors that affect benefit delivery (such as infrastructure, vulnerabilities, substitute availability, or ability to access ecosystem services) were only considered in 35% of assessments. Still, most research that applies disaggregation focuses on beneficiary groups and space, and very few examples exist for disaggregation by value types and time. Most studies disaggregate by only one dimension (but see for example: Arias-Arévalo et al., 2017; Brooks et al., 2014). In addition to the relatively small number of relevant case studies, some of which we presented in Table 1, existing conceptual frameworks can also contribute to a better understanding of the disaggregation of ecosystems services. Some frameworks assess the contribution of ecosystems to human well-being with specific attention to stakeholders and access mechanisms (Daw et al., 2016; Felipe-Lucia et al., 2015; Fisher et al.,

2014; Lele and Srinivasan, 2013; Martín-López et al., 2019; Reed et al., 2013; Robinson et al., 2019), or focus on the spatial assessment of ecosystem service flows (Bagstad et al., 2013; Koellner et al., 2019; Liu et al., 2013; Schröter et al., 2018; Serna-Chavez et al., 2014). Only few conceptual examples are concerned with broadening the scope of ecosystem service valuation (Chan et al., 2012; Iniesta-Arandia et al., 2014; Martín-López et al., 2014; Pascual et al., 2017) or the temporal dimensions of ecosystem services (Hein et al., 2016b; Rau et al., 2018).

Recent literature reviews (Bennett et al., 2015; Mandle et al., 2020) agree that the four dimensions we suggest are important for progress in ecosystem service science and policy making, but they remain underresearched. Bennett et al. (2015) identify as key research areas understanding the diversity of stakeholders (including their benefits and preferences for valuing) as well as identifying spatial patterns and temporal dynamics of ecosystem services use and benefit. The review by Mandle et al. (2020) shows that disaggregation by space, beneficiaries and value types is relevant, but understudied.

We acknowledge that there may be other important aspects of ecosystem service appropriation that could be disaggregated. However, we focus on these four dimensions of disaggregation because we believe they are the most directly useful for assessing the equity implications of ecosystem service appropriation. There is considerable benefit in the coherence of focusing on "who benefits in which ways across space and time". The equity implications of other possible dimensions that could be disaggregated (for example, the governance regime under which appropriation occurs, the stability of ecosystem service supply, or the cultural norms of appropriating groups) tend to be more focused on the broader social-ecological context that shape who benefits in which ways (across space and time). This sort of disaggregation suggests a quite different, but no less important, research question (i.e. why do particular patterns of appropriation occur?). However, here, we decide to focus on disaggregation within a particular social-ecological context and concentrate on the four dimensions suggested above.

Conducting disaggregated analyses of ecosystem services comes with many challenges. The best approach may depend on the context of a particular case study, and not all dimensions of disaggregation can always be considered in depth. We acknowledge that not all ecosystem services research can, or should, study all dimensions of disaggregation. However, we argue that the concurrent study of multiple dimensions of disaggregation is crucial, because understanding their interdependencies is vital for the sustainable management of ecosystem services. In the next sections, we show how disaggregation can be approached. For each of the four dimensions, we discuss conceptual issues, methodological approaches, and possible interactions with the other dimensions.

3.2. Beneficiary groups

Disaggregation by beneficiary groups is useful in identifying equity issues related to the appropriation of ecosystem services. It is also crucial to understand the power and interests of the different beneficiary groups and in which ways they benefit from ecosystem service flows (see also section 3.3 on value types below). When disaggregating by beneficiary groups, there is a strong rationale for focusing on the power (Felipe-Lucia et al., 2015) or influence and interest (Martín-López et al., 2019) that different beneficiary groups may have in shaping appropriation of ecosystem services. The dominant logic of the ecosystem service cascade (Haines-Young and Potschin, 2010) assumes that once we understand the benefits arising from natural resources, we can optimize their management to maximize the aggregate flow of benefits to society. However, this view neglects power dynamics and related management issues, such as who gets to decide which ecosystem services are optimized in the landscape. This is especially important when making decisions connected to land use, which implies trade-offs between ecosystem services (see for example Foley et al., 2005): depending on who gets to decide, different land-use regimes might be favored that are not socially desirable (this relates to procedural equity, for an example on procedural and other types of equity in the context of payments for ecosystem services see McDermott et al., 2013).

Understanding the relationship between ecosystem services and power is thus crucial when looking at beneficiaries of ecosystem services, however, a detailed discussion of the concept of power is beyond the scope of this paper (for further discussion on power see for example Lukes, 2005). Power dynamics related to ecosystem services have often been discussed in the context of payments for ecosystem services (see for example Ishihara et al., 2017; van Hecken et al., 2015). The framework by Felipe-Lucia et al. (2015), however, is a useful example that extends the ecosystem service cascade framework to include stakeholders' power relationships and roles. To analyze power dynamics related to ecosystem services, different factors can be in focus: stakeholders' ability to use, manage or impair ecosystem services (Felipe-Lucia et al., 2015), or their dependence on ecosystem services as well as their level of influence in decision-making (Martín-López et al., 2019). Such approaches can be connected to Q methodology in order to identify tensions between different beneficiary groups regarding which (and in what quantities) ecosystem services ought to be appropriated (Maniatakou et al., 2020). Social network analysis or the advocacy coalition framework can then help explain the dynamics that determine actual appropriation (Jiren et al., 2018; Weible et al., 2009).

To identify groups with different abilities to benefit from ecosystem services, a useful starting point is to identify distinct demographic and socioeconomic groups. People's ability to access ecosystem services is affected by factors such as their human capital stocks, endowments and entitlements, preferences, and the ability to achieve well-being by other means (Fisher et al., 2014). For example, wealthier households may be better positioned to take advantage of ecosystem services; similarly, activities related to the acquisition or use of ecosystem services may be considered gendered responsibilities (see for example Byg et al., 2017). Beyond the examples of gender and wealth, different beneficiary groups can be based on ethnicity, age, nationality, health status, residential type, education, income, social status, occupation, interest, opinion, or other characteristics. Comparisons between demographic and socioeconomic groups will reveal inequalities and distributional issues, but not necessarily the power they have to effect changes to the current appropriation regimes.

In general, there are two ways to approach disaggregation by demographic and socioeconomic groups. First, based on prior knowledge from the case study context or theory, ecosystem service appropriation can be analyzed for pre-determined groups, such as poor versus wealthy households (see Byg et al., 2017; Chaudhary et al., 2018). Second, a broader range of variables can be examined post-hoc, including variables describing socio-economic status that are used to develop socioeconomic groups through, for example, hierarchical cluster analysis (see Dawson and Martin, 2015; Dorresteijn et al., 2017). We recommend that, if reasonable hypotheses on the expected heterogeneity can be formulated from the literature or pilot studies, to first analyze by predetermined groups. As a second step, the assumption of heterogeneity between the chosen groups can be cross-checked by analyzing the resulting distribution by other characteristics, and assess if they are also relevant in explaining heterogeneity. Conversely, if little previous knowledge on the context exists, it may be more suitable to start with a broader analysis to first derive clusters of potential beneficiary groups.

3.3. Value types

Beneficiaries ascribe diverse values, preferences and priorities to ecosystem services. We apply a largely anthropocentric view on values, where humans ascribe values to ecological structures and functions. Disaggregating values into different value types is important, because they are often incommensurate and cannot substitute each other. For example, the direct use value ascribed to subsistence goods differs from their exchange value at a local market: The (aggregate) market value of

teff (*Eragrostis tef*) may not directly reflect the direct use value to a hungry farmer (to learn more about livelihoods in smallholder landscapes in Ethiopia see Manlosa et al., 2019). Similarly, relational or cultural values associated with certain ecosystem services cannot be substituted by more cash income (Chan et al., 2018; Pascual et al., 2017). In many contexts, aggregating across such value types and translating them into monetary value is not appropriate, because important value and preference dimensions may be lost. In contrast, disaggregating diverse value types can highlight the numerous (and often incommensurate) dimensions in which ecosystem services contribute to well-being (see for example Arias-Arévalo et al., 2017; Inglis et al., 2021; Riechers et al., 2021).

To disaggregate the values ascribed to ecosystem services, different frameworks can be used as a starting point (for an overview see Jacobs et al., 2018). First, the Total Economic Value (TEV) framework distinguishes between use and non-use values (Turner et al., 2003). Second, the The Economics of Ecosystems and Biodiversity (TEEB) framework separates ecological, sociocultural and monetary values (TEEB – The Economics of Ecosystems and Biodiversity, 2010). Third, the Intergovernmental Platform of Biodiversity and Ecosystem Services (IPBES) framework differentiates between non-anthropogenic (intrinsic), instrumental and relational value dimensions (Díaz et al., 2015). However, this distinction neglects the variety of values that might be part of the instrumental value dimension. For example, a direct use value ascribed to an ecosystem service because smallholder households depend on it for subsistence is fundamentally different to exchange values that are ascribed throughout the value chain. However, they both fall into the dimension of instrumental values. Here, we propose to combine the TEV and IPBES frameworks into four value types: direct use values, exchange values, relational values, and intrinsic values – where direct use and exchange values unpack the instrumental dimension of values.

One additional distinction of value type disaggregation that may be of use in relation to the sustainable use of natural resources is between 'receiver' and 'donor' value (Grönlund et al., 2015) – where receiver value is the value ascribed to, or received via, the appropriation of ecological structures or functions, and donor value seeks to quantify the value of the resources required to generate the appropriated services. A similar set of receiver values may require very different amounts and types of donor value to generate those benefits. For example, one ton of wheat produced without external inputs (high labor donor value) versus one ton of wheat from intensive production (non-renewable energy resources). Donor values may be qualified via approaches such as emergy analysis (e.g. Ulgiati et al., 1994), or primary production based approaches such as HANPP analysis (Erb et al., 2009). Disaggregation between receiver and donor value provides both the 'costs' and 'benefits' of ecosystem service appropriation. This type of value disaggregation may be of particular relevance in relation to temporal disaggregation when the donor value required to generate ecosystem service flows is dependent on the depletion of natural capital stocks (see section 3.5 below).

When approaching disaggregation by value types, it is important to minimize assumptions on the values that people ascribe to ecosystem services. Rather, for each case study, stakeholders should be consulted as to which values they ascribe, prior to any other type of analysis or quantification. Generally, eliciting and prioritizing values is a valid approach that can generate valuable insights (see for example Arias-Arévalo et al., 2017; Martín-López et al., 2014), and there is no need to force a quantification of values. To make sure that different worldviews are incorporated, appropriate value elicitation methods should be used, including biophysical, monetary and socio-cultural assessment methods (for an overview of methods see for example Harrison et al., 2018). To elicit exchange values, value chain approaches (Gereffi et al., 2005; Thyresson et al., 2013) and monetary valuation techniques (Harrison et al., 2018) can be helpful. Direct use values are best analyzed by approaches based on livelihoods, which try to understand beneficiaries' relationships with nature, for example by analyzing contextual factors that mediate the relationship between ecosystem service provision and beneficiaries' well-being (see Horcea-Milcu et al., 2016). Socio-cultural valuation approaches are particularly helpful to elicit relational values (Albizua et al., 2019), but can also elicit and compare a range of different values. Particularly helpful in this context are concepts and methods related to shared and social values of ecosystem services (Felipe-Lucia and Comín, 2015; Kenter et al., 2015; Raymond et al., 2019), especially value formation and elicitation through deliberation (Kenter et al., 2016; Kenter et al., 2011). Finally, intrinsic value is the value something has in and of itself, without regard to any other ends (Callicott, 2006). Such values cannot be easily be quantified (see Brown, 1984, for a broader discussion on such 'held values'). However, such values can be expressed, for example through narrative approaches, Q methodology or ranking and rating exercises (see Arias-Arévalo et al., 2017; Inglis et al., 2021; Riechers et al., 2021). If they are part of the worldview of certain stakeholder groups, these values should be explicitly acknowledged (Jacobs et al., 2018).

The multiple types of values derived from ecosystem services are likely to be strongly related to the different beneficiary groups who appropriate ecosystem services. Beneficiaries' location (urban versus rural populations, Arias-Arévalo et al., 2017) or occupation (Brooks et al., 2014) may influence values or the importance that they attribute to ecosystems and their services. In particular, beneficiaries dependent on subsistence direct use of ecosystem services are likely to have significantly different interests in and influence on the management of social-ecological systems than those beneficiaries that are primarily receiving exchange value (see for example Daw et al., 2015). Such distinctions also strongly influence equitable outcomes related to changes in ecosystem service flows. For example, a consumer who can no longer purchase a commodity from a specific ecosystem can simply seek another source while a subsistence farmer reliant of direct use value is likely to have less options to maintain such value in the absence of that service. The relationship between beneficiary groups and value types is also strongly related to spatial scales of appropriation (see next section).

3.4. Space

While it is important to understand how different types of beneficiaries benefit from appropriation of ecosystem services and what types of values they ascribe to that appropriation, it is equally important to understand how those types of beneficiaries and values occur across space. The same sort of beneficiaries ascribing the same sort of values may have significantly different consequences for ecosystem management depending on if they are within the ecosystem or distal from it. For example, local and global consumers may have different power and interest regarding the sustainable management of an ecosystem. Therefore, disaggregating beneficiaries and values across space provides further important insights regarding the social sphere of ecosystem service appropriation.

The distribution and appropriation of ecosystem services varies across space. For example, geographical location of households and other biophysical factors in a landscape (including forests, rivers, infrastructure, terrain) may determine appropriation of ecosystem services, independent of other characteristics. In many situations, ecosystem services are appropriated in a different place (and by different people) from where they are generated, as they flow from the local up to the global scale (Liu et al., 2013; Schröter et al., 2018). Disaggregating the spatial scales at which ecosystem service are generated and appropriated helps to reveal the often-present spatial segregation of costs and benefits. Further analyzing spatially disaggregated ecosystem service flows can help to determine relevant stakeholders as well as their interest and influence in ecosystem service management (Martín-López et al., 2019).

Many aspects of ecosystem service appropriation may be spatially disaggregated: ecosystem service use, dependency, flows, contribution

to livelihood, benefits and values. Spatial disaggregation is more explorative than the previous two dimensions, because spatial scales are particularly context-dependent. In many situations, disaggregation between local, regional, national and global scale may be sensible; in others, scales would need to be adjusted for the given context. At least two spatial scales, however, seem to be key for provisioning ecosystem services (i.e. commodities): the local scale, often defined by direct consumption, and larger spatial scales that ecosystem services flow to through formal and informal markets. Due to many interactions of spatial scales with our other three dimensions, we suggest exploring the distribution of beneficiaries and value types in parallel, in order to determine meaningful spatial scales at which to differentiate.

Analyzing spatial ecosystem service flows can make apparent the distribution of benefits from ecosystem services, especially for long-distance flows. In this context, several frameworks are helpful: a generic one that analyzes the spatial connections between ecosystem service provisioning and benefiting areas (Serna-Chavez et al., 2014), a conceptual framework for telecoupled flows of ecosystem services between ecosystem service sending and receiving systems (Schröter et al., 2018), and the application of a telecoupling lens to assess how social relations across scales influence the supply and distribution of ecosystem services (Martín-López et al., 2019).

The spatial flow of ecosystem services interacts with other dimensions of disaggregation. For example, beneficiary groups are usually associated with a particular scale (e.g. smallholder farmers are usually associated with the local scale where ecosystem services are generated, or see Thyresson et al., 2013 for an example related to fisheries). Differences between urban and rural populations are often of interest in disaggregated studies, which lie at the intersection between beneficiary groups and space (Arias-Arévalo et al., 2017; Lapointe et al., 2020; Orenstein and Groner, 2014). Geographic and socioeconomic characteristics may also interact to shape which groups are able to access ecosystem services (Dorresteijn et al., 2017).

3.5. Time

While the previous sections have focused on who benefits in what ways across space, here we are interested in how those beneficiaries and benefits may change across time. The previous three dimensions of disaggregation (beneficiary groups, value types and space) are concerned with issues related to understanding intra-generational distribution of ecosystem services. Temporal disaggregation may either focus on issues related to the stability of such intra-generational flows (temporal dynamics), or seeks to assess inter-generational distributional issues by highlighting changes in the capacity of ecosystems to provide ecosystem services across generations. Most ecosystems service assessments provide a static analysis at one point in time (Abson et al., 2010; Renard et al., 2015). However, identifying likely changes in supply and demand for given ecosystem services provides important information regarding mismatches between supply and demand and, in conjunction with knowledge on appropriation across space and beneficiary groups, the likely winners and losers in future appropriation of ecosystem services.

Nevertheless, assessments of temporal dynamics do not in and of themselves represent a dimension of disaggregation. Rather, such temporal dynamics provide an additional contextual factor for disaggregation by beneficiaries, value types or across space (see for example Rau et al., 2018, 2019). In contrast, seeking to assess inter-generational distributional issues does constitute a crucial aspect of ecosystem services disaggregation. Here we suggest that a simple distinction can be made between two types of ecosystem service provision: flows of services that are generated from a non-declining stock of natural capital, and ecosystem service flows that are dependent of the liquidation of capital stocks (e.g. Guerry et al., 2015). The former can be considered inter-generationally just, the latter not. The failure to distinguish between stocks and flows in the provisioning of ecosystem services assessments is almost ubiquitous in ecosystem service analyses and this severely hampers our ability to conceptualize inter-generational equity issues in relation to the ecosystem services concept.

Ecosystem service analyses should assess whether ecosystem service flows are sustainable or not: does the appropriation require liquidation of capital stocks? Here we would note that there is a broad body of scientific literature that seeks to model or assess changes in natural capital (see Guerry et al., 2015; Pan and Vira, 2019), but this is often not directly linked to on-the-ground ecosystem service assessments. The distinction between sustainable and unsustainable ecosystem service flows can be made either by modelling changing capacity of an ecosystem to provide particular ecosystems services (see for example, Burkhard et al., 2014; Haines-Young et al., 2012), or via directly assessing changes in natural and human capital stocks associated with ecosystem service appropriation, or co-production (Hein et al., 2016a; Jones et al., 2016).

The temporal disaggregation, particularly in relation to persistence over time and liquidation of natural capital stocks, is likely to be strongly influenced by both the spatial scale and types of values associated with ecosystem services. The more distal the appropriators, the less pronounced are the feedbacks regarding degradation of natural capital (Eakin et al., 2014; Liu et al., 2013). Similarly, where the values appropriated are primarily in terms of exchange, there is a strong likelihood that the degradation of natural capital, at least at the local scale, will be unnoticed by the beneficiaries, unless such costs are reflected in the market prices of ecosystem services.

3.6. Visualization of disaggregated valuation

Disaggregated data introduces new complexity into decision making and needs to be communicated carefully. Moving away from simple figures of aggregate numbers requires new presentation approaches of more complex (i.e. disaggregated) information. The importance of visualizations is widely recognized in environmental policy and planning, because visualization plays a role in data-communication, influences decision making, public perception, public participation, and knowledge cocreation (Metze, 2020). We therefore stress the importance of visualizing the results of disaggregated assessments in a format that is accessible and relevant to practitioners and policy makers, as well as to other scientists. Evidence-informed guidelines are available to increase accessibility of graphics to non-experts, e.g. for climate scientists (Harold et al., 2016). As with any data visualization attempt, trade-offs exist between the completeness and the communicability of results: which information is really needed with respect to the communication goal and target audience, and how much information reduction is too much, in that it could bias the information conveyed (Böttinger et al., 2020)? However these issues are resolved, there is no substitute for testing visualizations and graphics with the target audience (Harold et al., 2016).

Here, we suggest just one option of visualization which may prove useful, namely balloon plots (Fig. 1). The figure we present here is based on fictive data to illustrate the visualization of complex disaggregated information across multiple dimensions. Such plots have some key advantages when visualizing complex disaggregated information across multiple dimensions.

First, balloon plots can visualize multiple dimensions and their interactions in a single figure. This makes complex disaggregated information readily accessible. In our example, we visualize fictive data of the importance of diverse value types ascribed to ecosystem services by beneficiary groups at different scales. The value dimension (x-axis) disaggregates different value types, such as exchange or relational values. The spatial dimension (y-axis) disaggregates different spatial scales. Here, we included the examples of local, regional, national and global scales, but these may need to be changed depending on context (for example, to even finer scales, such as plots). The disaggregation by beneficiaries is indicated by balloon colors. Such groups may, for example, include farmers, traders or consumers. Balloon sizes represent

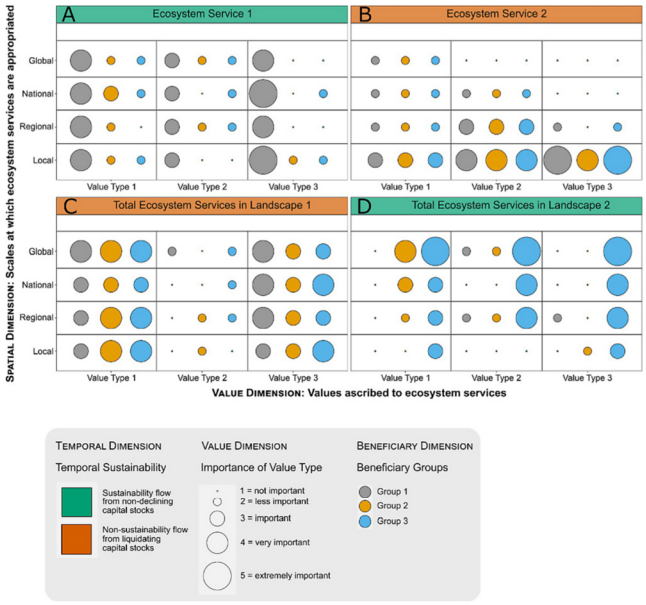

Fig. 1. The importance of diverse value types ascribed to ecosystem services by beneficiary groups at different scales. The figure here is based on fictive data to illustrate the visualization of complex disaggregated information across multiple dimensions.

the importance of each value type. They could, for example, be measured through a Likert scale-type assessment. Using such an assessment allows for the comparison of importance across value types and across different types of ecosystem services. We can also show whether appropriation is sustainable or unsustainable. Balloon plots thus seem appropriate to convey complex information on all four dimensions of disaggregation and their interactions.

Second, information in balloon plots is easily comparable across different ecosystem services, and trade-offs can be highlighted. In Fig. 1, we highlight differences between two ecosystem services (panels A versus B) and between aggregate ecosystem services in two landscapes (panels C versus D). For example, the importance of value types ascribed to ecosystem service 1 (panel A) is equally distributed across spatial scales and value types, but differs between beneficiary groups. For ecosystem service 2 (panel B), in contrast, all beneficiary groups ascribe similar importance to each value type, but importance decreases with spatial scale.

Visualizations through balloon plots thus allow for relatively easy comparison of complex information across ecosystem services or even landscapes, and can inform decision making on land cover and land uses, for example by highlighting trade-offs. Balloon plots therefore may be a valuable starting point to help convey disaggregated information on ecosystem service appropriation. Other types of visualization of course are also possible, depending on the information to be conveyed and the target audience.

4. A framework for disaggregation in ecosystem service research

We have discussed each of the four dimensions of disaggregation in turn, and how they interact with each other. As a starting point for designing new case studies that examine equity issues in the context of ecosystem service appropriation, in this section, we present a generally applicable, structured approach to assessing ecosystem services in a disaggregated way.

We acknowledge the role the IPBES framework can play as a first guideline towards disaggregation of ecosystem services. Seeing that the framework emerged to increase inclusivity and plurality in science and policy connected to the links between nature and people, it calls for a disaggregated understanding of beneficiaries and their values in space and time (Díaz et al., 2018; Kadykalo et al., 2019). However, to the best of our knowledge, a systematic approach to disaggregating ecosystem service appropriation and flows is lacking to date. Building on existing empirical and conceptual work, and our conceptual and methodological considerations above, we present a generally applicable, structured approach to assessing ecosystem services in a disaggregated way (Fig. 2). This approach can serve as a starting point for designing new case studies that examine equity issues in the context of ecosystem service appropriation.

The process of undertaking a disaggregated assessment of ecosystem services can be divided into four stages. Key questions that need to be considered in a disaggregated ecosystem service assessment serve as decision points within the flowchart. In Stage 1, the disaggregation context is identified, based on the equity issues that are most relevant in the case study context. Stage 2 consists of selecting the dimensions of the assessment, and the categories into which to disaggregate within each dimension. Here, care must be taken to balance the degree of disaggregation – key challenges are the analysis of interactions and the visualization of results from a multi-dimensional analysis. Trade-offs between detailed analysis and generalizability as well as data availability need to be considered. In Stage 3, appropriate methods to analyze disaggregation among the four dimensions should be selected and applied, matching the case study context. Stage 4 comprises multiple steps of synthesis and reflection. As discussed above, interactions between the dimensions should be assessed. Effectively visualizing the results is important to make insights accessible to decision makers and other scientists. As a last step, reflections on the results may lead to adjustments and re-iterations of earlier stages in the disaggregation assessment.

5. Discussion

In the previous sections, we have seen how to approach disaggregated ecosystem service assessments along four dimensions. In this section, we look more closely at their (potential) role in policy making,

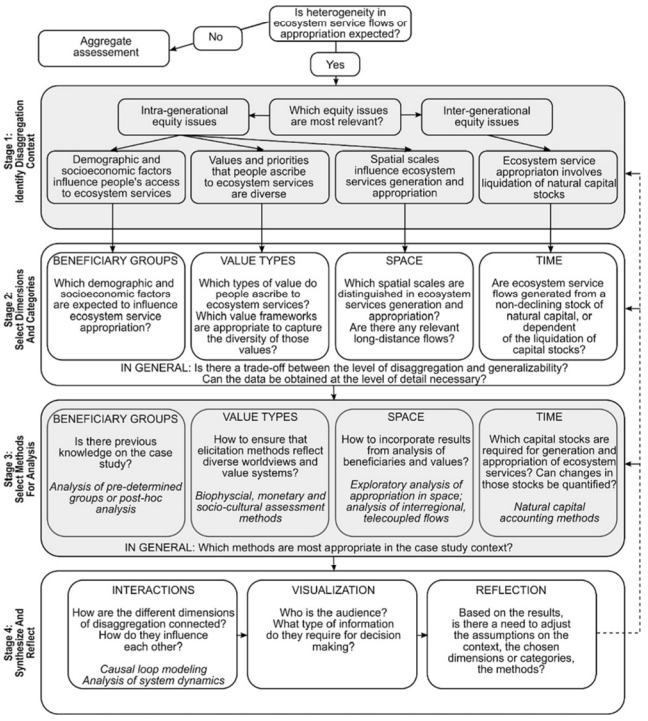

Fig. 2. Flowchart indicating key questions for the disaggregated assessment of ecosystem services.

and discuss how such analyses can promote an alternative understanding of ecosystem services as complex social-ecological phenomena.

Disaggregated analyses of ecosystem services are key to making ecosystem services research more relevant to decision making (Mandle et al. 2020, Fisher et al. 2014): they provide crucial and detailed information necessary to understand the consequences (across beneficiary groups, types of values generated, space and time) of changing natural resource management and ecosystem services appropriation. The results of disaggregated analyses can therefore help to alleviate intra- and intergenerational equity and sustainability concerns in natural resource management and governance.

Disaggregated assessments by *beneficiary groups* can highlight inequalities driven by power relations that influence the appropriation of ecosystem services (Felipe-Lucia et al., 2015; Lau et al., 2020; Martín-López et al., 2019). Additionally, such analyses help to understand access mechanisms (Daw et al., 2011; Fisher et al., 2014), and to identify the most vulnerable and ecosystem service-dependent groups (Ma et al., 2019; Martín-López et al., 2019). Such knowledge can feed into designing appropriate policies to prevent and alleviate poverty. An improved, disaggregated understanding of beneficiary groups, based on both equity concerns and power dynamics, helps to design policies that strengthen the appropriation of ecosystem services by disadvantaged groups.

Disaggregating ecosystem services by *value types* acknowledges a plurality of values and worldviews, and can thus contribute to integrated valuation approaches (Jacobs et al., 2018). Plural valuation, in turn, can contribute to more equitable and environmentally sustainable outcomes from decisions (Zafra-Calvo et al., 2020), by highlighting, for example, "taboo" trade-offs between morally incommensurable values (Daw et al., 2015). We acknowledge the importance and the benefits of plural valuation as proposed by IPBES (Pascual et al., 2017). However, how to make decisions based on plural valuation remains understudied. Categorization into different value types does not tell us much in practical terms when there are trade-offs between the value types, or/and when different beneficiaries place different relative importance on them. We therefore emphasize the importance of disaggregation based on multiple dimensions, including the analysis of power dynamics.

The *spatially disaggregated analysis* of ecosystem service appropriation can be integrated with analyses of mismatches in supply and demand (Burkhard et al., 2014), to enhance sustainable management of ecosystem service flows. Analyzing and visualizing ecosystem service flows may help to make the spatial distribution of benefits understandable to stakeholders and other interest groups. By connecting to research on interregional flows (Koellner et al., 2019; Schröter et al., 2018), spatial disaggregation supports the improvement of management tools (see examples of international conservation payments (Bagstad et al., 2019) or transboundary flood management agreements (Kleemann et al., 2020).

Finally, by including *temporal disaggregation* with respect to the ability of humans and ecosystems to continue to generate sustainable flows of services across time, disaggregated ecosystems services assessments can provide insights into inter-generational equity issues. Understanding temporal dynamics in the supply or demand of ecosystem services is of vital importance for their management (see Rau et al., 2018, 2019 for detailed discussions).

In addition to their contribution to policy making, disaggregated assessments may also form the basis for an alternative understanding of ecosystem services and their classification. The definition and classification of ecosystem services is an ongoing discussion point in the research field. The Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005), The Economics of Ecosystems and Biodiversity project (TEEB – The Economics of Ecosystems and Biodiversity, 2010), the Common International Classification of Ecosystem Services (Haines-Young and Potschin, 2018), and the Final Ecosystem Goods and Services Classification System (Landers and Nahlik, 2013) all propose classification systems of ecosystem services (Costanza et al., 2017). The IPBES has recently proposed eighteen categories of material, non-material and regulating nature's contributions to people (IPBES, 2019).

It has been suggested that classifications of ecosystem services should rather be based on the decision context and purpose of the assessment (Costanza, 2008; Fisher et al., 2009). Therefore, we suggest to complement (or even substitute) current classification systems by an approach that is based on the interactions between beneficiaries, values, space and time as a way of charactering ecosystem services. As such, ecosystem services can be understood as complex social-ecological phenomena, where the potential ecosystem service's character is not purely defined by its physical type (e.g. provisioning, regulating, cultural or supporting). Rather the character of services emerges via the complex interplay of social and economic structures and functions in a particular social-ecological system.

For example, while "coffee" might be traditionally understood as a provisioning ecosystem service, there is not really only one ecosystem service "coffee". In a local and subsistence-based economy, coffee may be collected, processed and consumed locally, without degrading natural capital. Such coffee may be valued by people for its direct use and relational values. In contrast, large-scale intensive coffee production, that degrades natural capital largely, generates exchange values possibly only for a small number of local people, while simultaneously connecting very different beneficiaries via global trade. This shows again how beneficiaries, values and spatial scales interconnect, and how changing production and trade patterns may fundamentally alter the types of values and beneficiaries associated with the appropriation of that service. In turn, when making decisions on land use and related ecosystem services, it might for example be more useful to distinguish between (and assess differently) locally used and globally traded coffee, instead of referring to coffee as one uniform ecosystem service.

Based on the results of a disaggregated analysis of ecosystem services, new categories of ecosystem services might emerge, which can provide an alternative way of thinking about the appropriation of ecosystem services, both in research and policy making. In some cases, such distinctions could be more important and useful than the distinction of "traditional" MEA types of ecosystem services.

6. Conclusion

This paper is a step towards making disaggregation of ecosystem services more prominent both in research and policy making. The four disaggregation dimensions proposed in this paper – namely beneficiary groups, value types, space, and time – can help to better assess the equity implications of ecosystem service appropriation. Such forms of disaggregated ecosystem service assessment are vital in the shift away from a focus on 'optimization' of ecosystem service supply based on a single metric of value. We propose instead a more nuanced understanding of ecosystem services as complex social-ecological phenomena. In doing so, we challenge traditional approaches to the categorization and assessment of ecosystem services that are insufficiently focused on the challenges of sustainable natural resource management. We hope that our flowchart with key questions to consider in disaggregated assessments can serve as a starting point for future empirical work. By discussing the suitability of balloon plots to convey complex disaggregated information, we have provided some guidance on how to appropriately communicate such results to decision makers. This can help to make natural resource management more sustainable.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Chapter III: Drivers of ecosystem service specialization in a smallholder agricultural landscape of the Global South: a case study in Ethiopia

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Research

Drivers of ecosystem service specialization in a smallholder agricultural landscape of the Global South: a case study in Ethiopia

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ABSTRACT. The global shift toward agricultural specialization in the 20th century led to unprecedented ecological and socioeconomic changes, both positive and negative, in rural landscapes. Economic theory describes comparative advantage and market participation as two important drivers of such changes. Landscapes in the Global South are still often characterized by subsistence agriculture and direct dependence on natural ecosystem processes. Agricultural specialization is part of the structural transformation process from subsistence to market-oriented agriculture. However, comparative advantage and market participation as major drivers for agricultural specialization remain understudied. In this paper, we assess the potential drivers of ecosystem service specialization in an Ethiopian smallholder landscape at the kebele level, the smallest administrative unit in Ethiopia. We measured specialization via the concentration of production for a range of locally important provisioning ecosystem services (beef, cattle, coffee, eucalyptus, honey, maize, sorghum, and teff). We measured comparative advantage based on productivity data, and assessed spatial flows of ecosystem services to local, regional, and global markets (i.e., telecoupling). To unpack the relationships between specialization, comparative advantage, and telecoupling, we used hierarchical clustering, principal component analysis, correlation analysis, and linear regression. More telecoupled kebeles (i.e., kebeles that produced more of ecosystem services that flow to broader spatial scales) were more specialized in their ecosystem service production, and the positive relationship between comparative advantage and specialization grew stronger with altitude. Wealthier kebeles and kebeles with higher population density were less specialized. Biophysical drivers, such as altitude and amount of forest cover, influenced the ecosystem services produced and the relationship between comparative advantage and specialization. Policy makers should therefore try to balance potential positive and negative consequences of specialization, and to account for fine-scale social and biophysical drivers underpinning diverse ecosystem service production profiles.

Key Words: *agricultural specialization; comparative advantage; ecosystem service flows; Ethiopia; land management; smallholder agriculture; telecoupling*

INTRODUCTION

A key shift in agricultural practices during the 20th century in rural landscapes around the world has been the increase in agricultural specialization, leading to unprecedented changes in the ecological and socioeconomic characteristics of these landscapes (Abson 2019). Although agricultural specialization can increase agricultural yield and food productivity (Tilman 1999, Godfray et al. 2010), specialization also comes with potentially negative consequences, including declines in biodiversity and increased ecological externalities such as water pollution or greenhouse gas emissions (Stoate et al. 2009, Abson 2019). Moreover, agricultural specialization can increase vulnerability to ecological and economic shocks because of decreased multifunctionality and resilience (Foley et al. 2005, Fischer et al. 2017, Abson 2019, Frei et al. 2020), and often leads to landscape simplification, which can negatively impact biodiversity (Abson 2019), or human-nature connectedness and relational values (Riechers et al. 2022). Finally, specialization can also cause social problems, such as rising inequalities and the erosion of values, traditions, and local knowledge (Jiren et al. 2020a, Schultner et al. 2021, Riechers et al. 2022), with the danger of leaving behind groups that are already disadvantaged, for example because of their lack in capital assets or agency (Manlosa et al. 2019a, Schultner et al. 2021, Manlosa 2022).

Economic theory describes comparative advantage and market participation, often also termed "commercialization," as two important drivers of agricultural specialization (Abson 2019). Comparative advantage is the ability of an economic agent to carry out a particular economic activity more efficiently (at a lower relative opportunity cost) than another agent (Watson 2017). This provides a strong economic rationale for farmers and governments to favor large-scale, specialized agricultural production of tradable goods for which they have a comparative advantage (Abson 2019). Associated benefits for farmers and societies include higher profits and increased resource efficiency (Matsuyama 1992, Hunt and Morgan 1995). Comparative advantage therefore allows greater production with lower resource use and production costs, potentially freeing resources for other socially useful purposes (Green et al. 2005, Godfray and Garnett 2014). Market access and participation are pre-conditions for the exploitation of comparative advantages, because the process of specialization depends on global commodity markets for both inputs and outputs. Hence, a lack of transportation infrastructure or other forms of market access can limit or slow the agricultural specialization process (Li et al. 2017, Abson 2019). Moreover, the extent of the market drives specialization, because a larger market allows greater specialization by ensuring adequate demand for specialized products; this idea dates back to Adam Smith (Emran and Shilpi 2012, Li et al. 2017). In addition to comparative advantage and market participation, a range of social and biophysical variables, such as wealth or landscape diversity, might also explain agricultural specialization (Table 1).

Despite its obvious importance, agricultural specialization, and especially its relationship with market participation and comparative advantage, remains poorly understood in

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Table 1. Variables used in analysis, including their definition and expected relationship with specialization. Kebele (smallest administrative units in Ethiopia) production data were adjusted for kebele area and scaled by a robust scaler (i.e., the median is subtracted from each datapoint, then divided by the interquartile range). Kebele productivity data were also robust scaled. For additional details see Appendix 1. ES = ecosystem services, LULC = land use land cover.

Variable	Definition	Expected relationship with specialization
Specialization	Concentration of ES production; Simpson's index (infinite version) based on kebele production data (area adjusted, robust scaled)	-
Telecoupling	Degree of market connection to broader spatial scales in terms of ES production; Telecoupling score for each ES (average number of beans weighted by degree of telecoupling of each spatial scale) multiplied by total annual ES production for each ES, summed across ES	POSITIVE: Markets ensure adequate demand for large-scale production and access to necessary inputs (Li et al. 2017, Abson 2019). Studies in Ethiopia have shown that an increase in walking distance from markets or roads increases the likelihood and extent of crop diversification (Mussema et al. 2015, Dessie et al. 2019).
Comparative advantage	Concentration of ES productivity; Simpson's index (infinite version) based on kebele productivity data (robust scaled)	POSITIVE: Farmers and societies obtain benefits from specializing in goods for which they have a comparative advantage and trading them, such as higher profits and increased efficiency (Abson 2019).
Biophysical variables		
Mean altitude	Calculated from a digital elevation model with 30m resolution	UNCLEAR: Coffee grows naturally in the region at altitudes between 1500 and 2100 m (Dorresteijn et al. 2017, Duguma et al. 2022) and forest cover decreases with altitude (one reason is forest clearing in altitude ranges that are unsuitable for coffee; Hylander et al. 2013). Yet ultimate influence unclear: Lower forest cover and the absence of coffee might mean that kebeles at higher altitudes show more specialization because they cannot produce any coffee. On the other hand, kebeles in coffee growing altitudes might specialize in coffee production.
Forest cover	Forest area divided by total kebele area (in ha)	UNCLEAR: See mean altitude.
Landscape diversity	Simpson's diversity index based on absolute area (in ha) of 12 LULC classes	UNCLEAR: The relationship between ES multifunctionality and land use diversity is complex, and depends on the location, choice of indicator, and scale of analysis (Stürck and Verburg 2017).
Remoteness	Sum of distance from the nearest town and distance from the nearest road (both robust scaled)	NEGATIVE: With greater distance from markets, farmers need to rely on a diverse set of ecosystem services for subsistence, because they cannot trade outputs or inputs in markets (Mussema et al. 2015, Dessie et al. 2019).
Social variables		
Share of women in the population	Number of women divided by total population	UNCLEAR: Women are more risk averse and tend to promote a more diversified and food secure approach to ecosystem service production (Assefa et al. 2022, Sekyi et al. 2023). On the other hand, it has been shown that male-headed households tend to increase farm diversification because they have better access to required resources (Asante et al. 2018, Dessie et al. 2019, Manlosa et al. 2019c).
Population density	Total population divided by total kebele area	UNCLEAR: The higher population density, the smaller farm sizes (Josephson et al. 2014). Some studies have shown that in Ethiopia larger farm size is associated with higher diversification (Mussema et al. 2015, Kidane and Zegeye 2018, Mekuria and Mekonnen 2018, Dessie et al. 2019), whereas a recent global meta-analysis found that smaller farms have higher crop diversity (Ricciardi et al. 2021).
Wealth	Number of tin roofs divided by total number of households	UNCLEAR: Farmers who hold more (durable) assets are more likely to specialize (Li et al. 2017, Sekyi et al. 2023). Studies in Ethiopia found however that livestock ownership, which is a significant capital asset in Ethiopia (Manlosa et al. 2019b), is positively associated with diversification (Kidane and Zegeye 2018, Mekuria and Mekonnen 2018).

smallholder agricultural landscapes of the Global South (Li et al. 2017, Sekyi et al. 2023). These landscapes are often characterized by subsistence agriculture and direct dependence on local ecological resources, such as fuelwood or crops for personal consumption (Tallis et al. 2008, Egoh et al. 2012). Agricultural specialization is part of the structural transformation process from subsistence to market-oriented agriculture (Emran and Shilpi 2012, Li et al. 2017). In this context, pursuing a comparative advantage approach seeks to optimize profits via efficient resource allocation, but it does not necessarily address issues related to risk and diversification in agroecological systems. For example, some studies have investigated the consequences of agricultural specialization, or of its opposite, diversification, suggesting that crop diversification is positively associated with higher household income (Pellegrini and Tasciotti 2014, Bellon et al. 2020), higher food security (e.g. in terms of higher self-consumption of food crops) and dietary diversity (Pellegrini and Tasciotti 2014, Waha et al. 2018, Manlosa et al. 2019a, Bellon et al. 2020), and lower risk of poverty (Michler and Josephson 2017).

Others have explored drivers of specialization or diversification in countries of the Global South in relation to household, farm, or regional characteristics, such as gender of household head, farm size, or distance to markets (Li et al. 2017, Asante et al. 2018,

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Mekuria and Mekonnen 2018, Dessie et al. 2019). Only a few studies have explicitly analyzed the relationship between specialization, market participation and comparative advantage. Most studies that analyzed the relationship between crop or crop-livestock specialization and market participation found a positive relationship between them (Mussema et al. 2015, Li et al. 2017, Dessie et al. 2019, Sekyi et al. 2023). In contrast, some found a negative relationship (Mekuria and Mekonnen 2018, Rampersad 2021), or a U-shaped relationship (Emran and Shilpi 2012). Studies that focused on comparative advantage or productivity found a positive relationship between crop specialization and productivity (Kurosaki 2003, Kidane and Zegeye 2018, Sekyi et al. 2023). Most of the studies focused on the household or farm level and on crops or livestock, but Emran and Shilpi (2012) analyzed specialization at the village level, and Torres et al. (2018) considered a range of different ecosystem services, including some from agroforestry systems and coffee.

In this paper, we analyze potential drivers of agricultural specialization in a smallholder landscape in southwestern Ethiopia, with a particular focus on market participation and comparative advantage. In the study area, livelihood strategies have traditionally been diversified and subsistence-oriented (Manlosa et al. 2019a). Specialization and market integration are, however, strongly encouraged by the government, and many stakeholders, such as farmers and representatives of governmental, non-governmental, and civil society organizations, expect or even favor such developments (Federal Democratic Republic of Ethiopia, National Planning Commission 2016, Jiren et al. 2020a, 2020b). Over the past decades, production has already begun to shift from subsistence to marketed crops, and access to cash crops with indirect benefits (e.g., economic returns from trade) increased (Schultner et al. 2021). In this way, the economy in the landscape and the local farmers' livelihoods are increasingly shaped by the flow of global commodities such as coffee (Petit 2007).

We frame our analysis of potential drivers of agricultural specialization in terms of the ecosystem services concept and focus on provisioning ecosystem services. These are defined as the products obtained from ecosystems, including, for example, food, fuel, and water (Millennium Ecosystem Assessment 2005). We use the ecosystem services concept here to highlight that instead of merely being agricultural products, the "ecosystem services" in our case study fulfill multiple roles, such as providing cultural meaning and determining other non-provisioning services. Kebeles, the smallest administrative units in Ethiopia, in our study area differ in their social and biophysical characteristics as well as in the ecosystem services they produce (Dorresteijn et al. 2017, Duguma et al. 2022), and local people's livelihoods strongly depend on ecosystem services (Dorresteijn et al. 2017, Manlosa et al. 2019a). From previous research, we know that a number of provisioning services, such as maize and coffee, are important to local people (Dorresteijn et al. 2017, Manlosa et al. 2019a, Shumi et al. 2019). Because trade-offs often occur between provisioning services and regulating or cultural services (Raudsepp-Hearne et al. 2010, Martín-López et al. 2012), provisioning services are likely to determine (via trade-offs or synergies) other ecosystem services that are generated in the landscape, as well as socioeconomic and equity outcomes (Brück et al. 2022). For example, increasing commercialization of provisioning ecosystem services in the landscape will change land use patterns overall, which could cause deforestation and thus the loss of regulating and cultural services for the landscape as a whole (Kassa et al. 2017, Schultner et al. 2021). Moreover, benefits and values associated with provisioning services are likely to change if production becomes more specialized and market-oriented, that is, changing from direct use toward exchange values, with important implications for livelihoods and well-being (Daw et al. 2011, Brück et al. 2022). Whereas increased economic capacity may enable some households to purchase goods and make livelihood investments, lack of economic capital may prevent other households to make initial investments for participation in market-oriented cropping (Schultner et al. 2021).

The degree of market participation of farmers has been defined as the degree of production for markets as opposed to production for subsistence (Emran and Shilpi 2012, Li et al. 2017). To define and describe the degree of market participation, we use the concept of telecoupling, which describes "both socioeconomic and environmental interactions among coupled human and natural systems over distances" (Liu et al. 2013), and has been broadly implemented by researchers from diverse disciplines (Hull and Liu 2018, Kapsar et al. 2019). In the context of ecosystem services, the telecoupling concept has for example been used to analyze water governance (Liu et al. 2016), spatial subsidies of migratory species (López-Hoffman et al. 2017), or power asymmetries and social relations related to ecosystem services (Martín-López et al. 2019). Based on the telecoupling concept, Schröter et al. (2018) and Koellner et al. (2019) provided guidance on how to analyze interregional ecosystem services flows, leading us to focus here on the "biophysical flows of traded goods" (Schröter et al. 2018).

The overarching goal of this paper is to explore potential drivers of ecosystem service specialization in an Ethiopian smallholder landscape, including telecoupling, comparative advantage, and other potentially important social and biophysical factors. This paper addresses two key gaps in the literature, we (1) focus our analysis on telecoupling and comparative advantage in relation to specialization, which are theoretically important drivers for specialization during the process of agricultural structural change, but have not received much attention in case studies of the Global South, and (2) choose the kebele level as unit of analysis instead of the household level.

Analyzing the relationships between specialization, telecoupling, and comparative advantage provides a better understanding of a key, but context-specific driver of land use change, which is in turn a major driver of biodiversity loss and multiple social and economic outcomes (for example, the access to, and distribution of, key ecosystem services). Focusing on the municipal or kebele level, rather than individual households' responses to telecoupling and comparative advantage, provides important insights at the landscape level, and thereby can help inform policy interventions to mitigate against land use homogenization and the associated risks of ecological and market shocks (Abson and Termansen 2011, Abson et al. 2013). We analyze ecosystem services that are relevant in the landscape, rather than only focusing on crops and/or livestock production (beef and cattle as well as maize, sorghum, and teff, but also coffee, eucalyptus, and honey). We draw on two strands of literature where we see the possibility for mutual

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learning, one that is centered around notions such as "agricultural diversification/specialization," "market participation," and "commercialization" (Emran and Shilpi 2012, Li et al. 2017, Kidane and Zegeye 2018), and the other around "ecosystem service multifunctionality" and "telecoupling" (Hölting et al. 2019, Frei et al. 2020, Llopis et al. 2020).

To achieve our goal, we (1) define indices to quantify specialization, telecoupling, and comparative advantage in each kebele, (2) examine correlations between specialization, telecoupling, and comparative advantage across all kebeles in the study area, (3) analyze how these relationships differ between kebeles in three farming type clusters, and (4) build a regression model to statistically test the role of telecoupling and comparative advantage, and other social and biophysical variables, as possible drivers of specialization. With this paper we thereby makes the following contributions: we operationalize the telecoupling concept in an ecosystem services context by measuring ecosystem service flows to spatial scales from the household to the global level in a data-scarce environment; in a case study region in Ethiopia, we empirically assess potential drivers of agricultural specialization, based on ecosystem service production and flow data; and we produce results that may help policy makers better understand possible future landscape change and therefore make more informed decisions about ecosystem service management. In this way, we contribute to a broader understanding of how telecoupling and comparative advantage may act as drivers of specialization during the process of agricultural structural change in the Global South.

METHODS

Study area

The study area consisted of three woredas (districts), in Jimma Zone, Oromia Region, Ethiopia, namely Gera, Gumay, and Setema woreda (Fig. 1). The landscape is a recognized biodiversity hotspot (Mittermeier et al. 2011) and characterized by a mosaic of farmland and moist evergreen Afromontane forest (Hylander et al. 2013). Smallholders are mainly involved in subsistence farming, which provides diverse ecosystem service benefits to the local community (Shumi et al. 2019, Schultner et al. 2021), but also ecosystem services of global importance, such as carbon storage (De Beenhouwer et al. 2016). Kebeles in the study area measure on average 30 km² and have an average population of approximately 4000 inhabitants.

Data collection and validation

We collected and analyzed data for 61 rural kebeles with multifunctional land uses in our study area. Seventeen kebeles in our study area were excluded from analysis because they were dominated by forests or large towns (see Appendix 1 for details). Important ecosystem services in the landscape include those stemming from the use of woody plants, inter alia eucalyptus (*Eucalyptus* spp.) and honey (Shumi et al. 2019); coffee (*Coffea arabica*) as one of the main cash crops; and maize (*Zea mays*), sorghum (*Sorghum bicolor*), and teff (*Eragrostis tef*) as key food crops (Manlosa et al. 2019a). Households usually own a small number of livestock, and the most valuable of these are cattle, which are used as draft animals and also considered a valuable capital asset (Manlosa et al. 2019b). We distinguished between cattle used for general purposes versus cattle used specifically for beef fattening (i.e., for meat production). We thus collected data for the following eight ecosystem services: eucalyptus, honey, coffee, maize, sorghum, teff, cattle, and beef.

In October and November 2020, we conducted interviews on ecosystem service production and flows with experts in woreda offices in Gera, Gumay, and Setema. Experts were chosen based on their respective expertise. For example, experts working at the Bureau of Agriculture were asked about cereal crop production and flows. For ecosystem service production, we collected mainly official data from the experts for all ecosystem services, and where unavailable relied on experts' estimates (for details see Appendix 1). For each kebele, we collected total annual production (cattle/beef: number owned, coffee/honey/maize/sorghum/teff: ton, eucalyptus: m³) and area dedicated to the production (in ha; honey: number of producers) for each ecosystem service. Missing values for some kebeles for beef, coffee, eucalyptus, and sorghum production and area were imputed based on the data from other kebeles (for details see Appendix 1). The collected data were cross-checked for plausibility and consistency with remote sensing data, secondary productivity data, and data from previous research (for details see Appendix 1).

Official data on ecosystem service flows, that is, information on how much of a given ecosystem service stays within households or flows to broader geographical scales, was difficult to obtain, especially at relatively fine scales like the household and kebele level. For this reason, we used a "coffee bean exercise" to elicit this knowledge (for details see Appendix 1). For this, experts were asked to allocate 20 coffee beans (representing a household's yearly yield of the ecosystem service) to different spatial scales, in order to spatially disaggregate proportionate flows for each ecosystem service studied (Fig. 2). We defined five spatial scales based on local understandings of the supply chain: household, local market (kebele), district market (woreda), central market (regional/national), and global market. We collected this information for all ecosystem services for a selection of 12 kebeles representing social-ecological gradients in the study area. Kebeles in our study area were clustered into four social-ecological groups, based on a range of ecological and social variables. We then chose a sub-set of kebeles, three from each of the four social-ecological kebele groups.

Definition of variables

All data analysis was conducted using R version 4.1.2 (R Core Team 2021; main R packages used are indicated in the text, information on additional packages can be found in Appendix 1). We adjusted ecosystem service production data by kebele area to account for kebele size differences, and applied a robust scaler (a scaling method that is relatively insensitive to outliers, where the median is subtracted from each datapoint, then divided by the interquartile range) to facilitate direct comparison among diverse ecosystem services. For each ecosystem service, we divided total annual production by the area dedicated to the production (in ha; honey: number of producers) to obtain ecosystem service productivity. Kebele productivity data were then also robust scaled. Our analysis included three main variables (specialization, telecoupling, comparative advantage; Fig. 3) plus a range of social and biophysical variables that we expected might explain

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Fig. 1. Map of (A) the location of the study area in Jimma Zone, Oromia, Ethiopia; and (B) a detailed view of the three woredas, including kebeles (smallest administrative units in Ethiopia) boundaries and altitude (from ASTER digital elevation model with 30m resolution, obtained from https://asterweb.jpl.nasa.gov/gdem.asp; NASA/METI/AIST/Japan Spacesystems and U.S./Japan ASTER Science Team 2009, Duguma et al. 2022).

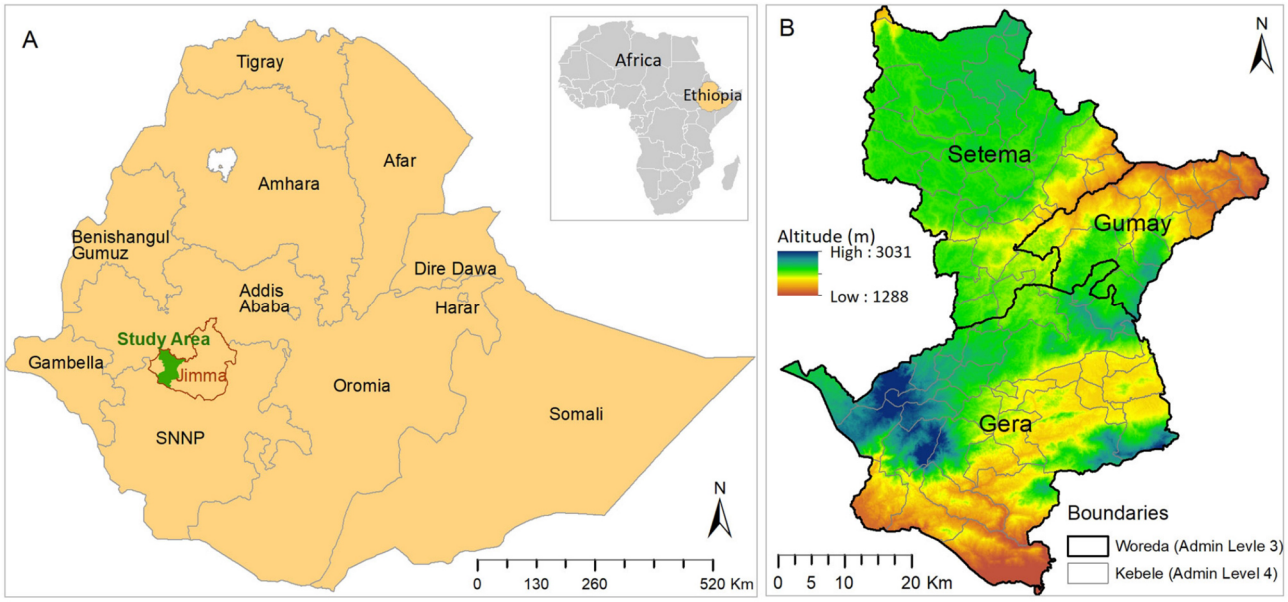
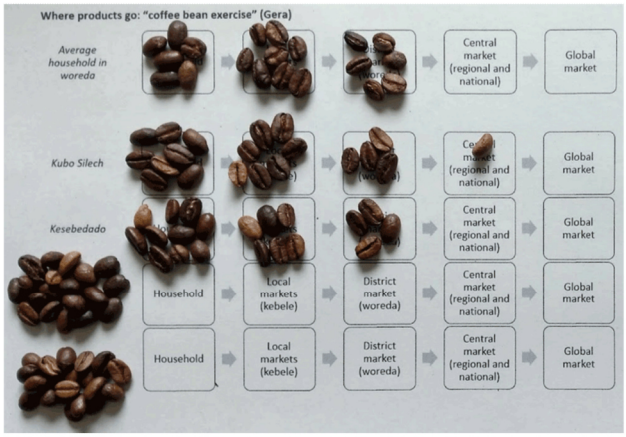


Fig. 2. Coffee bean exercise to elicit ecosystem service flow data. Experts allocated 20 coffee beans (representing a household's yearly yield of the ecosystem service) to five spatial scales: household, local market (kebele), district market (woreda), central market (regional/national), global market. Each row represents a different kebele within the woreda (district).



specialization (Table 1). Other variables may also play a role in driving specialization, such as farmers' agency or cultural norms. However, such variables are difficult to measure, and their examination would require more extensive research.

In our definition, a kebele was more specialized if its ecosystem service production was more concentrated and less evenly distributed across services. That is, a kebele that produced a lot of some ecosystem services and only comparatively little of other ecosystem services had a higher specialization score than a kebele that produced the same amount of all ecosystem services. We measured the degree of specialization for each kebele through Simpson's index (for infinite samples) based on ecosystem service production data for each kebele (gini.simpson.C in R package diverse, v0.1.5, Guevara et al. 2016). We chose this index, which takes into account both richness and evenness, instead of other diversity indices, because it is a very meaningful and robust diversity measure and provides good estimates at relatively small sample sizes (Magurran 2011), it reflects best the nature of our data, and it has been widely used in the literature on ecosystem service multifunctionality (Raudsepp-Hearne et al. 2010, Brandt et al. 2014, Stürck and Verburg 2017, Hölting et al. 2019, 2020).

Similarly, we defined that a kebele was more telecoupled if it produced more of relatively highly telecoupled ecosystem services than other kebeles. Our telecoupling score thus indicated how connected a kebele was to broader spatial scales in terms of its ecosystem service production. We measured the degree of telecoupling for each kebele by a combination of data on average ecosystem service flows to different spatial scales, and ecosystem service production data for each kebele. Based on the "coffee bean exercise," we calculated the average number of coffee beans attributed to each spatial scale for each ecosystem service (across the 12 kebeles), and weighted the different spatial scales by their degree of telecoupling (household scale = 0, local = 1, district = 2, central = 3, global = 4; see Fig. 2) to obtain a telecoupling score

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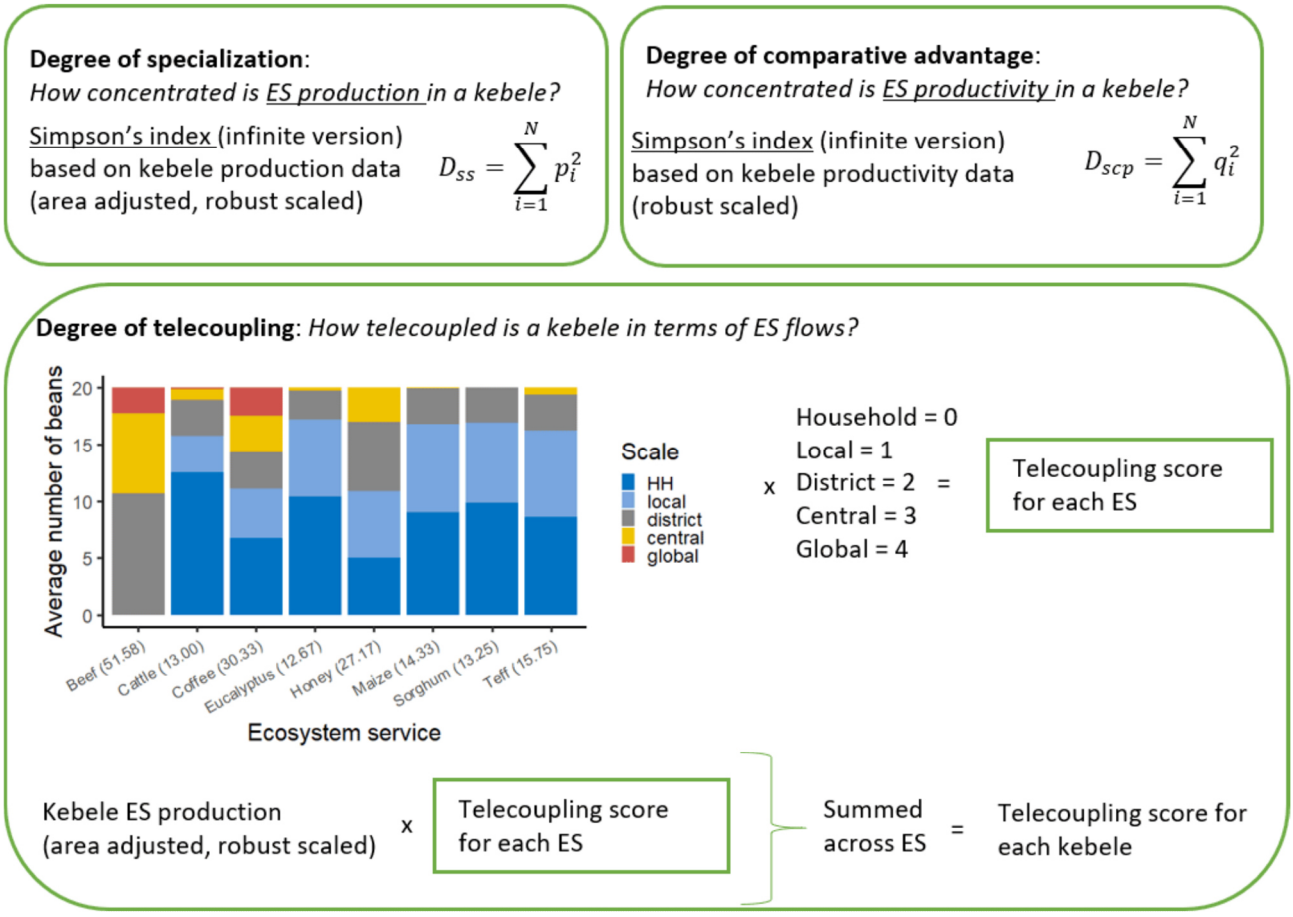
Fig. 3. Definition and calculation of the three main variables: specialization, telecoupling, and comparative advantage. Kebele (smallest administrative units in Ethiopia) production data were adjusted for kebele area and scaled by a robust scaler, i.e., the median is subtracted from each datapoint, then divided by the interquartile range (IQR). Kebele productivity data were also robust scaled. ES = ecosystem services; Dss = Simpson's index based on ES production, measures specialization; N = total number of ecosystem services considered; pi = share of total annual production of ES i in the total annual production of all ES in the kebele; Dscp = Simpson's index based on ES productivity, measures comparative advantage; qi = share of productivity of ES i in the sum of productivities of all ES in the kebele. For example, the value for kebele Bore Dedo for cattle was 13,680, which was then divided by the total kebele area (2688.1318 ha), which gives 5.09 cattle/ha. The median of all kebeles for the kebele area adjusted cattle was 4.17, and the IQR was 4.81. The resulting value (adjusted for kebele area, robust scaled) for Bore Dedo for cattle was thus (5.09-4.17)/4.81 = 0.19.



for each ecosystem service. We then multiplied this score by total annual production for each ecosystem service and summed across ecosystem services to obtain a telecoupling score for each kebele.

A kebele had a higher comparative advantage if its ecosystem service productivities were more concentrated and less evenly distributed. That is, a kebele that was very productive in producing one or more particular ecosystem service(s) and less productive in producing others had a higher comparative advantage score than a kebele that produced all ecosystem services with similar (high or low) efficiency. A higher score thus meant a local comparative advantage for one (or few) ecosystem services within the kebele compared to the other ecosystem services, and hence theoretically more incentive for farmers to specialize. We measured the degree of comparative advantage for each kebele through Simpson's index based on ecosystem service productivity data.

Data analysis

To assess associations between specialization, telecoupling, and comparative advantage, we performed a correlation analysis. Because the variables were not normally distributed (Shapiro-Wilk test: $p < 0.001$ for all three variables), we chose to analyze correlation by the Kendall rank correlation coefficient τ (Kendall 1938, 1949, Kruskal 1958, Newson 2002).

To understand how the relationships between our main variables differed between kebeles, we explored if kebeles could be meaningfully grouped based on their ecosystem service

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production. We performed a hierarchical clustering analysis based on (robust scaled) production data for all eight ecosystem services (Euclidean dissimilarity matrix, Ward's clustering method). The resulting dendrogram was then classified into clusters (representing farming types) based on visual inspection, considering group interpretability (for dendrogram see Fig. A1.1).

To assess if telecoupling and comparative advantage were significant predictors of specialization, and to explore the role of other potential social and biophysical drivers for specialization, we built a linear regression model with specialization as the dependent variable (for details see Appendix 1). As explanatory variables, we included telecoupling and comparative advantage, additional biophysical and social explanatory variables, as well as two-way interactions between comparative advantage, landscape diversity, and mean altitude, based on the results of the kebele clustering as well as prior knowledge on the study area (see Equation 1, Table 1, and for further details on the two-way interactions, Appendix 1). We first conducted thorough data exploration (following the protocol by Zuur et al. 2010), and centered and scaled all independent variables. We applied a Box-Cox transformation to the dependent variable, and Yeo-Johnson transformations to telecoupling, comparative advantage, female population, landscape diversity, and remoteness to account for non-linearity, non-normality, and heterogeneity in the data, using the bestNormalize package (v1.8.2, Peterson 2021). We then fit a "full" model, defined as:

$$\text{Specialization}_i = \beta_0 + \beta_1\,\text{Telecoupling}_i + \beta_2\text{Comparative advantage}_i + \beta_3\text{Mean altitude}_i + \beta_4\text{Forest cover}_i + \beta_5\text{Landscape diversity}_i + \beta_6\text{Remoteness}_i + \beta_7\text{Share of female population}_i + \beta_8\text{Population density}_i + \beta_9\text{Wealth}_i + \beta_{10}\text{Comparative advantage}_i * \text{Mean Altitude}_i + \beta_{11}\text{Comparative advantage}_i * \text{Landscape diversity}_i + \beta_{12}\text{Mean altitude}_i * \text{Landscape diversity}_i + \varepsilon_i \quad (1)$$

For kebele i, where β_0 is the intercept, β_1 to β_{12} are the parameters to be estimated, and ε_i is the error term with $\varepsilon \sim N(0, \sigma^2)$. To find the most parsimonious explanatory model, we then applied stepwise backward model selection based on the Akaike information criterion (AIC) and validated the final model (checking for linearity, normality of residuals, homogeneity of variance, outliers and leverage points, autocorrelation, and multicollinearity), using ggfortify (v0.4.13, Tang et al. 2016) and gvlma packages (v1.0.0.3, Pena and Slate 2021). To check if our main variables of interest, telecoupling, and comparative advantage were significant predictors to the model, we compared models with and without these variables using ANOVA at a significance level of $\alpha = 0.05$.

To check the robustness of our correlation analyses and the linear model to alternative definitions of our focal indices, we computed different versions of our main variables (for details see Appendix 1). For telecoupling, we varied the weights applied to the spatial scales. For specialization and comparative advantage, we calculated a range of alternative diversity indices. We checked if imputed data had a significant influence in the linear model, by checking if dummy variables for imputed value had a significant influence on the model results.

Our study has some limitations. First, data were partly based on experts' best estimates and thus may be biased. To minimize the risk of bias, we cross-checked ecosystem service production data against remote sensing, secondary, and household-based data of previous project research, and averaged ecosystem service flow data across 12 kebeles. Second, we only focused on provisioning services here, because they are of key importance to local people; future studies should examine if and how our findings translate to other types of ecosystem services. Last, other studies have shown a two-way causality between specialization and market participation, which we refer to as telecoupling in this paper (Emran and Shilpi 2012, Li et al. 2017, Sekyi et al. 2023). However, we chose specialization as our main and dependent variable of interest because of its important implications for the livelihoods of smallholder farmers.

RESULTS

The spatial distribution of flows differs between ecosystem services

Based on experts' assessments, on average, more than half of a household's yearly yield of almost all ecosystem services (except beef) stayed in the household or at the kebele level (Fig. 4). Beef was the ecosystem service with the highest telecoupling score, followed by coffee and honey.

Ecosystem service specialization is positively correlated with both telecoupling and comparative advantage, but kebele farming types influence these relationships

Hierarchal clustering of ecosystem service production data resulted in three clusters of kebeles, denoting three different farming types (Fig. 5). Kebeles in the first cluster ("beef") produced significantly more beef, and kebeles in the second cluster ("coffee/honey") significantly more coffee and honey than kebeles in the other clusters (Fig. A2.2). Kebeles in the third cluster ("mixed") produced significantly more cattle, eucalyptus, maize, sorghum, and teff than kebeles in the other clusters. Beef cluster kebeles had significantly higher altitudes and lower forest cover than the other two clusters (Fig. A2.3).

We found a strong positive and significant correlation between telecoupling and ecosystem service specialization across kebeles ($\tau = 0.33$, $p < 0.001$; Fig. 6), and a positive significant relationship between comparative advantage and ecosystem service specialization across kebeles ($\tau = 0.19$, $p = 0.03$). These correlations were robust to outliers and different versions of our variables (Fig. A2.1, A2.4, A2.5).

Robust to different versions of our variables (Fig. A2.4), the beef and the mixed cluster both showed positive significant relationships between telecoupling and ecosystem service specialization (beef: $\tau = 0.28$, $p = 0.016$; mixed: $\tau = 0.35$, $p = 0.052$; Fig. 6), though the relationship was not significant in the coffee/honey cluster. In contrast to the significantly positive general correlation between comparative advantage and ecosystem service specialization, none of the individual clusters showed a significant correlation between these variables (Fig. A2.5).

Telecoupling, comparative advantage and altitude significantly contribute to predictions of specialization

Robust to different versions of our variables (Table A2.1, A2.2, A2.3, A2.4), the final model with specialization as the dependent variable (Table 2; adjusted $R^2 = 0.331$, $F(6,54) = 5.945$) showed positive significant relationships for telecoupling ($\beta = 0.66$; $p < 0.001$), and the interaction between altitude and comparative advantage ($\beta = 0.33$; $p = 0.065$; Fig. 7). The mean main effect of altitude was positively significant ($\beta = 0.21$; $p = 0.083$), whereas comparative advantage on its own was not significant, but had a

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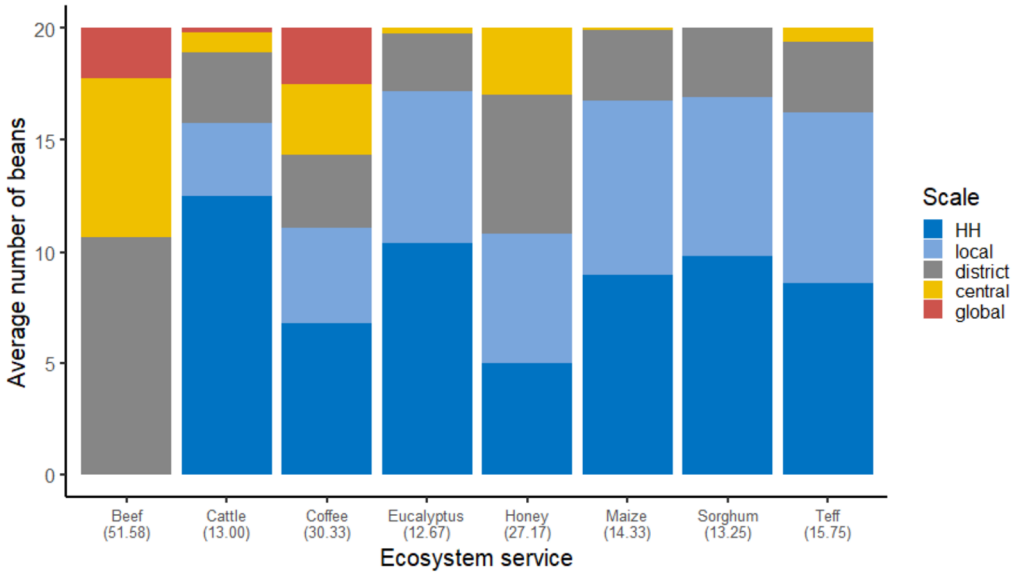
Fig. 4. Bar chart indicating average number of coffee beans (across 12 kebeles, smallest administrative units in Ethiopia) attributed by experts to each spatial scale for each ecosystem service. Twenty coffee beans represented a household's yearly yield of the ecosystem service. Telecoupling score for each ecosystem service in brackets (average number of coffee beans weighted by degree of telecoupling of each spatial scale, and summed across spatial scales). HH = household.



positive coefficient. Population density and wealth showed negative significant relationships (β = -0.35, p = 0.018; β = -0.25, p = 0.026). Telecoupling and comparative advantage, our main variables of interest, significantly contributed to predictions of specialization (ANOVA; F(3, 49) = 7.1257, p < 0.001; for details and additional checks showing that they were significant predictors see Appendix 2).

DISCUSSION

Methodological contribution

In a data-scarce environment, we operationalized the telecoupling concept in the context of ecosystem services through spatial disaggregation of ecosystem service flows (see Liu et al. 2016, López-Hoffman et al. 2017, Boillat et al. 2018 for other examples). Because ecosystem services are often appropriated at different places and by different people than where they are generated, it is crucial to consider spatial scales when analyzing ecosystem services (Hein et al. 2006). Spatial disaggregation of ecosystem service flows helps to understand where ecosystem services are generated versus where they are appropriated, and can hence serve as a proxy for understanding who benefits from the ecosystem services generated in a given landscape (Brück et al. 2022). We used a "coffee bean exercise" as an alternative data collection method, in order to assess ecosystem service flows in a data-scarce environment, and measured the degree of telecoupling for each kebele by a combination of data on average ecosystem service flows to different spatial scales, and ecosystem service production data. Using coffee beans or other types of tokens is an established data collection method, for example for the assessment of ecosystem service importance (Hicks et al. 2015, Lau et al. 2018), or as a triangulation method for measurements of sensitive, socially undesirable behavior (Lau et al. 2011, Jones et al. 2021). Our results concerning the degree of telecoupling of kebeles were only made possible through this participatory data collection method, because official data on ecosystem service flows at fine spatial scales were not available.

Telecoupling is a positive significant predictor of ecosystem service specialization

Telecoupling was correlated with specialization across all kebeles, and in two of three kebele farming type clusters (Fig. 6), we found a significant positive relationship for telecoupling in our linear model (Table 2), and showed that a model with telecoupling and comparative advantage as explanatory variables was significantly better than a model without them: hence, more telecoupled kebeles were more specialized in their ecosystem service production. The exception in the coffee/honey cluster (no significant correlation) can either be attributed to the fact that this cluster contained only few datapoints, or to social and cultural factors connected to coffee production. Our study thus confirmed a pattern that has already been observed in agricultural landscapes of the Global North and in some studies for the Global South: agricultural specialization and market participation are closely related (Emran and Shilpi 2012, Li et al. 2017, Abson 2019). Some Ethiopia-specific studies are in line with our findings, showing that crop diversity at the household level increased with distance to markets or roads (Mussema et al. 2015, Dessie et al. 2019). In contrast, other studies in Ethiopia found that crop-livestock or crop diversity at the household level increased with market access (Mekuria and Mekonnen 2018, Rampersad 2021). These results show that the effects of more telecoupling (higher market

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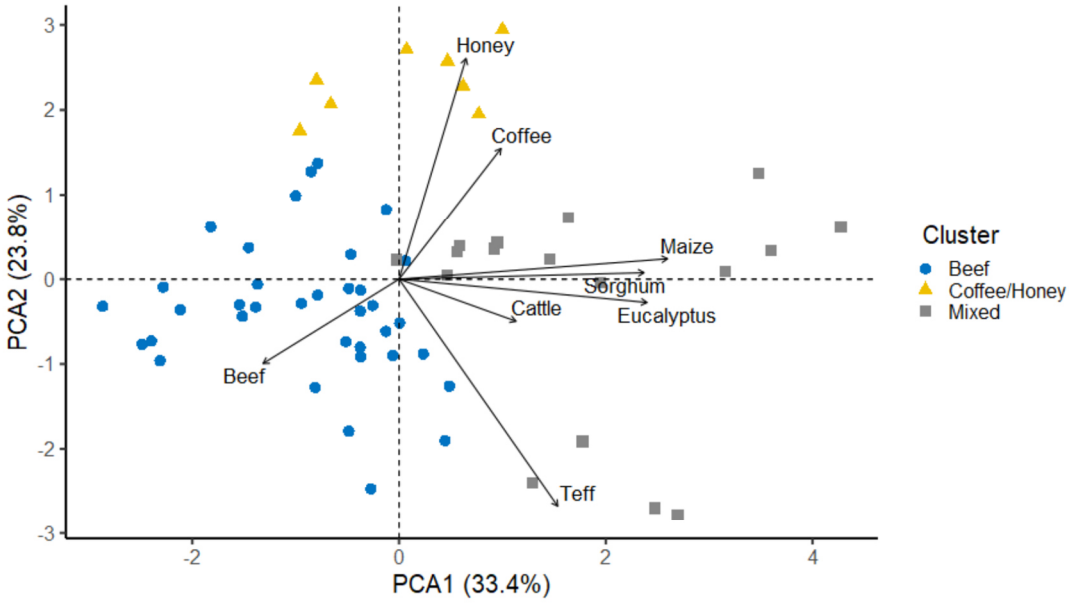
Fig. 5. Ordination plot of kebele (smallest administrative units in Ethiopia) farming types. Clusters based on hierarchical clustering analysis of ecosystem service production data of eight ecosystem services for 61 kebeles, and visualized by principal component analysis (PCA). Each datapoint represents one kebele. The x-axis represents the first principal component (explains 33% of the variation). The y-axis represents the second principal component (explains 24% of the variation). Arrows show ecosystem service production. Longer arrows mean stronger correlation with PCA axes. Clusters were determined from visual inspection of dendrogram after hierarchical clustering of ecosystem service production data and named according to the ecosystem services they are mainly defined by.



participation or access) very much depend on the case study specific context, for example, with regard to the types of crops or livestock investigated, the definition of market participation, or the stage of specialization. Emran and Shilpi (2012) found, for example, a U-shaped causal relationship between the extent of the market and the pattern of crop specialization, suggesting that the portfolio of crops in a village economy becomes more diversified initially, however, after the market size reaches a threshold, the production structure becomes more specialized.

The agricultural landscape in our study area might thus be on a trajectory to face similar opportunities and challenges of increased specialization and market integration as other highly specialized landscapes, such as rising incomes but also increased vulnerability to ecological and economic shocks through loss of redundancy, adaptive capacity, and response diversity (Abson 2019, Walker et al. 2023). However, despite marked differences in specialization between kebeles, we should also note that the overall degree of specialization in the study area is (until now) relatively low.

Comparative advantage, altitude, and their interaction influence ecosystem service specialization

Comparative advantage was positively correlated with specialization across all kebeles (but not within specific farming types; Fig. A2.1); it was a significant positive predictor for specialization in its interaction with altitude (but not on its own; Table 2), and a model with telecoupling and comparative advantage as explanatory variables was significantly better than a model without them; hence, there was a relationship between comparative advantage and specialization, but it was weaker than for telecoupling. Only a few studies examined the relationship between specialization and comparative advantage or productivity in the Global South. Among these, Sekyi et al. (2023) found that crop specialization positively related to agricultural productivity (measured in crop produced per hectare) in a case study in Ghana, whereas Kidane and Zegeye (2018) found that crop diversification had a negative but non-significant influence on productivity in Ethiopia. In our analysis, kebeles in higher altitudes were typically more specialized, on average, but this positive relationship was most pronounced in kebeles with high comparative advantage, and relatively minor in kebeles with low comparative advantage (Table 2, Fig. 7).

From our cluster analysis and the linear model, we observed an interplay of altitude with forest cover and ecosystem service production in the kebeles of our study area (Fig. 5, A2.2, A2.3). Kebeles at higher altitudes had lower forest cover and produced more beef, and tended to specialize more (mostly in beef production). Kebeles of lower altitudes, in contrast, had higher forest cover and produced either forest ecosystem services or a mixture. Although lower altitudes are suitable for coffee, which is a global commodity of considerable value, it was interesting that these kebeles did not specialize in coffee production, but rather included coffee in a diverse portfolio of ecosystem services production. Other studies in our study area have already

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Fig. 6. Scatterplot for 61 kebeles (smallest administrative units in Ethiopia) of the relationship between telecoupling and ecosystem service specialization, with density plots by clusters "beef," "coffee/honey," and "mixed." The density plots (around the edges of the plot) represent the distribution of specialization and telecoupling, and help to visualize the distribution of the two variables for each cluster. Specialization was measured by Simpson's index based on ecosystem service production data, and telecoupling by a combination of ecosystem service production data and weighted average ecosystem service flow data.

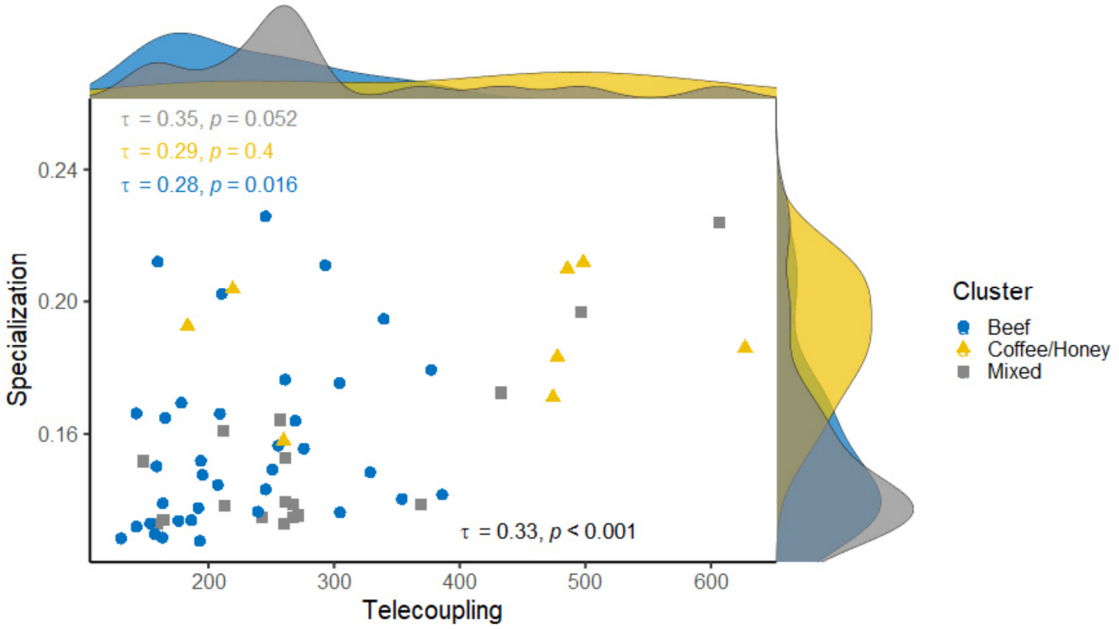

Table 2. Results of the linear model testing the influence of social and biophysical kebele (smallest administrative units in Ethiopia) characteristics on ecosystem service specialization. All predictor terms were continuous. Specialization was measured by Simpson's index based on ecosystem service production data, telecoupling by a combination of ecosystem service production data and weighted average ecosystem service flow data, and comparative advantage by Simpson's index based on ecosystem service productivity data.

Term	Specialization		
	Coefficient	Standard error	P-value
Intercept	-0.01	0.10	0.931
Comparative advantage	0.19	0.13	0.159
Telecoupling	0.66 ***	0.15	<0.001
Mean altitude	0.21 *	0.12	0.083
Population density	-0.35 **	0.14	0.018
Wealth	-0.25 **	0.11	0.026
Comparative advantage*Mean altitude	0.33 *	0.18	0.065
Observations	61		
R^2 / R^2 adjusted	0.398 / 0.331		

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

demonstrated that location (altitude and proximity to forest) is an important driver of ecosystem services distribution (Dorresteijn et al. 2017), and that people depend on forest ecosystem services, but that access to them is decreasing (Shumi et al. 2019, Schultner et al. 2021).

Biophysical conditions (such as altitude and forest cover) and limited tenure security and use rights in the study area may restrict smallholders' agency to change their ecosystem service production, especially if they belong to poor or already vulnerable groups (Shumi et al. 2019, Manlosa 2022). Kebeles at lower, coffee-suitable altitudes did not exploit comparative advantages as much as kebeles at higher altitudes. Social or cultural factors may explain why coffee productivity plays a minor role in farmers' decision to produce or specialize in coffee. In contrast to most other ecosystem services that we analyzed, coffee showed no positive correlation between its production and productivity (Fig. A2.6), and it could be associated with numerous socio-cultural benefits (Bulitta and Duguma 2021).

Population density and wealth are negative significant predictors of ecosystem service specialization

Population density had a significant negative relationship in our model (Table 2), meaning kebeles with higher population density tended to specialize less. Farm sizes usually decrease with higher population density (Josephson et al. 2014), and many studies at the household level in the Global South found that larger farm sizes can lead to higher diversification, thus smaller farm sizes should lead to specialization (Benin et al. 2004, Mussema et al. 2015, Li et al. 2017, Kidane and Zegeye 2018, Mekuria and Mekonnen 2018, Torres et al. 2018, Dessie et al. 2019), which seems to contradict our results. In contrast, a recent meta-analysis across 55 countries and 154 crops found that smaller farms had higher crop diversity (Ricciardi et al. 2021), which would support our finding. However, these previous studies focused on the household level in the context of crop or crop-livestock

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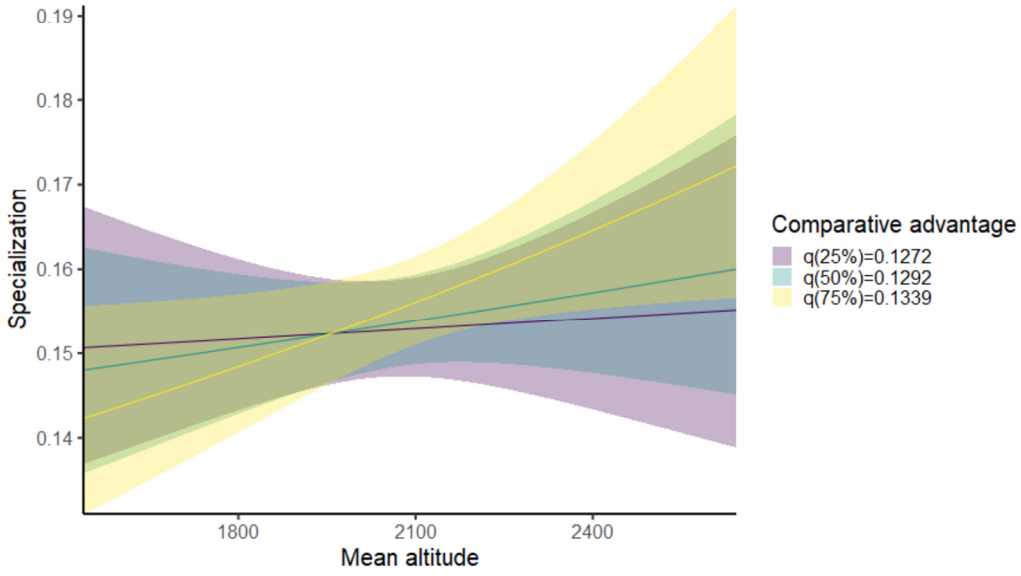
Fig. 7. The relationship between mean altitude and specialization, and its interaction with comparative advantage. Predicted values of specialization based on mean altitude, with 95% confidence interval. For 25%, 50%, and 75% quantiles of comparative advantage and all other variables set to their mean value.



diversification; only Torres et al. (2018) considered a range of different ecosystem services, including some from agroforestry systems and coffee. Our analysis, in contrast, examined patterns at the kebele level, and we are not aware of any prior investigations for Ethiopian landscapes at this level for forest and woody vegetation-based ecosystem services (in our case: coffee, eucalyptus, and honey).

In our case, higher population density might mean more opportunities to exchange or trade with other people in the kebele (our data showed that for all ecosystem services, except beef, more than half of household production stayed in the kebele or the household; Fig. 4). Therefore, each household might specialize in different ecosystem services, but with a maintenance of an overall diverse production in the kebele that allows households to trade and exchange.

Wealth was a significant negative predictor in our model (Table 2), meaning that wealthier kebeles tended to be less specialized in their ecosystem service production. There is no obvious way to define wealth (for example, some studies looked at durable assets, others at livestock ownership as a proxy), and here we used the proportion of tin roofs as a proxy for wealth (Duguma et al. 2022; Table 1). Again, as for patterns of vegetation-based ecosystem services diversity at the kebele level, no prior data exist, to the best of our knowledge, at the village or kebele level for the relationship between wealth and specialization or diversification, and evidence at the household level is mixed. Some studies showed that farmers who held more (durable) assets were more likely to specialize (Li et al. 2017, Sekyi et al. 2023). Studies in Ethiopia found, however, that livestock ownership, which is a significant capital asset in Ethiopia (Manlosa et al. 2019b), and larger land holdings were positively associated with diversification (Kidane and Zegeye 2018, Mekuria and Mekonnen 2018), which is further supported by our results. Wealthier kebeles may thus be able to "afford" diversity and not only focus on few subsistence crops that are needed for more immediate survival.

Implications for policy making

Knowledge on the dynamics between ecosystem service specialization, comparative advantage, and telecoupling is useful to plan for a rapidly changing future landscape. Even though ecosystem service specialization in the study area remains relatively low, we found a strong relationship between telecoupling and specialization, and some evidence for a relationship between comparative advantage and specialization. The government and many other stakeholders favor development toward specialization, intensification, and market integration (Jiren et al. 2020b). In this study, we showed that telecoupling and (to some extent) comparative advantage drive specialization in the landscape, and we know that increased specialization is a likely future development in the study area (Jiren et al. 2020a). However, agricultural specialization comes with economic and ecological trade-offs at different spatial scales (Klasen et al. 2016). Potential negative consequences of specialization include increased vulnerability to ecological and economic shocks due to decreased multifunctionality and resilience (Foley et al. 2005, Fischer et al. 2017, Abson 2019, Frei et al. 2020); decreased food security and higher poverty risk (Pellegrini and Tasciotti 2014, Michler and Josephson 2017, Waha et al. 2018, Manlosa et al. 2019a, Bellon et al. 2020); decline in biodiversity and rise in ecological externalities (Stoate et al. 2009, Abson 2019); and increased social problems such as rising inequalities and the loss of local traditions and knowledge (Jiren et al. 2020a, Schultner et al. 2021, Riechers

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et al. 2022). A diversification strategy, on the other hand, could mean to forego the benefits associated with specialization and market integration, such as higher efficiency, yield, and profits (Pellegrini and Tasciotti 2014, Abson 2019).

These considerable potential positive and negative consequences of specialization require informed decisions regarding land use and ecosystem services. The role of farmers in land governance in our study area is limited, and is for example restricted by limited tenure security and land use rights (Shumi et al. 2019, Manlosa 2022). Governance related to ecosystem service management is often strongly hierarchical, and dominated by government administrative organizations, which can lead to power capture, where the interests of few powerful stakeholders override those of smallholder farmers (Jiren et al. 2018, 2022). However, participatory and collaborative governance can be a means to tackle environmental problems in a sustainable way (Newig and Fritsch 2009, Jager et al. 2020). Despite the currently limited role of smallholder farmers in governance in the case study landscape, we hope to strengthen the sustainable future development of the landscape by bringing back results of our research to local communities, and by helping to engage policy processes that involve actors from all levels, including smallholder farmers (Fischer et al. 2018, Jiren et al. 2020a, Jiren et al. 2023).

One example of specific policies in the context of ecosystem service management concerns the future of coffee in the study area, and the decision whether to prioritize southwestern Ethiopia for export coffee production (hence increased specialization and telecoupling), or to establish a biosphere reserve that combines sustainable agriculture, eco-coffee production, and tourism opportunities (Jiren et al. 2020a). Policy makers should consider smallholders' heterogeneity (in livelihood strategies, capital assets, access to ecosystem services, and agency), and ensure that especially already disadvantaged groups are able to benefit from structural changes to their livelihoods (Manlosa et al. 2019a, Jiren et al. 2020b, Schultner et al. 2021, Manlosa 2022). An example are poor, landless men, who have, in their position as labor-contributing share-croppers, less decision-making power regarding the crops to plant (marketable vs. subsistence crops), with direct implications for their food security (Manlosa 2022). We also found that biophysical factors such as altitude and forest cover influenced specialization directly and played a role in the relationship between comparative advantage and specialization. Kebeles should thus not be managed uniformly or based on administrative groups, but rather based on their unique social and biophysical characteristics (Hanspach et al. 2016, Oberlack et al. 2019).

CONCLUSION

The goal of this paper was to explore drivers of ecosystem service specialization in an Ethiopian smallholder landscape. Based on data on ecosystem service production, productivity, and flows for each kebele, we found that both telecoupling and comparative advantage were positively significantly correlated with specialization. More telecoupled kebeles were more specialized in their ecosystem service production, and the positive relationship between comparative advantage and specialization grew stronger with altitude. Different factors thus drive specialization in the study area, and at the same time, developments toward specialization, intensification and market integration are encouraged by the government and expected or supported by many stakeholders. Policy makers should try to balance potential positive and negative consequences of specialization, especially for already disadvantaged groups, such as landless people. Kebeles should not be managed uniformly, but policy making should consider biophysical differences such as altitude and forest cover, because such factors determine to a large extent which ecosystem services are produced and how comparative advantage and specialization develop and interact. We encourage other researchers to employ novel data collection methods if official data cannot be obtained. Through our "coffee bean exercise" we were able to disaggregate ecosystem services flows from the household to the global level and, ultimately, to gain important insights for the smallholder landscape under study. Our analysis of an Ethiopian case study contributed to a broader understanding of how telecoupling and comparative advantage act as drivers of specialization during the process of agricultural structural change in the Global South.

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Data Availability:

The data and code that support the findings of this study are openly available in https://pubdata.leuphana.de/ at https://doi.org/10.48548/pubdata-6. The study was not approved by an institutional ethics review committee. In the expert interviews, we did not obtain personal information, but rather collected official data and expert estimates of ecosystem services flows.

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Appendix 1: Methods

Methods: Data collection and validation

Kebele selection

Of the overall 78 kebeles in the study area we excluded state forest kebeles (12 kebeles), two kebeles with a forest share larger than 90%, and three towns. The state forest kebeles and the two kebeles with a very high forest share (larger than 90%; Gemina Dacho and Gere Ifalo) were excluded, because in this research we are interested in multifunctional, mixed-use agricultural landscapes. The three kebeles that have more than 30% of their total area dedicated to towns were excluded (Chira town, Gatira town and Toba town – one located in each woreda), because they function differently than the rural kebeles that our analysis is focused on.

Challenges of the data collection process

Obtaining the required data on ecosystem service production at the woreda and kebele level was challenging and time-consuming. Such sub-national data needs to be obtained from experts in person, because no online data is available. For some ecosystem services, there was only little official data available, which meant that we had to rely on experts' estimates (roughly 40% of all datapoints). We even dropped some ecosystem services from the analysis, because too little datapoints could be obtained.

Data imputation and cross-check

For beef, we did not collect area data, but instead asked for the main source of fodder, because we had no previous data on how beef fattening cattle in the landscape was fed. Experts indicated that beef fattening cattle were mostly grazing. We thus inferred the area for beef for each kebele by rule of three based on cattle data. Rule of three is a mathematical rule that allows you to solve problems based on proportions, such as $a/b = c/x$. To calculate x, we can use: $x = (b*c/a)$. For six kebeles for which no data on coffee were provided, we assumed that no coffee is grown in these kebeles, because they are all outside of optimal or potential coffee growing zone. For six kebeles for which no data on eucalyptus were provided, we imputed area values based on the relationship between eucalyptus area to share of woody vegetation in each woreda, and based on this, production values from average woreda productivity for eucalyptus. For two kebeles for which no data on sorghum were provided, we imputed sorghum area based on the ratio of maize and teff area to sorghum area in each woreda, and based on this, production values from average woreda productivity for sorghum.

Data was cross-checked for plausibility and potential outliers. For this, we compared the sums across kebeles with woreda data, compared area data with remote sensing data, and cross-checked productivity of all ecosystem services with secondary data and household-based data of previous project research (Dorresteijn et al. 2017, Manlosa et al. 2019, Shumi et al. 2019). We decided to not exclude any data points.

Coffee bean exercise

In this exercise, experts were asked to allocate 20 coffee beans (which represent a household's yearly yield of the ecosystem service) to different spatial scales to spatially disaggregate ecosystem service flows. Note that for beef and cattle we used two differing interpretations. For beef, the 20 beans represented the share of the herd that is sold in each year, because they are only of value to

local people when they are sold. For cattle, the 20 beans represented the entire herd owned by a household, because cattle provide a continuous use value to the household (as draft animals). We defined five spatial scales based on local understandings of the supply chain: Household, Local market (kebele), District market (woreda), Central market (regional/national), Global market. We collected this information for all ecosystem services for a selection of 12 kebeles representing social-ecological gradients in the study area, four from each woreda.

Detailed description of instructions.

- Please introduce the exercise like this: "*In this exercise, I would like to get your expert opinion on where agricultural products from the woreda flow. We will talk about the following agricultural products: cattle, cattle for beef fattening, coffee, eucalyptus (in three sizes), firewood, honey, khat, maize, sorghum, and teff. Please have a look at this picture* [show the printed-out figure]. *The different squares represent different scales. First, you can see the household level. The other squares represent the local market (kebele), district market (woreda), central market (region and national) and global market."*

[For each agricultural product:]

- *"Here we have 20 coffee beans* [place 20 coffee beans in household square]. *They represent an average household's yearly harvest/yield of* [insert agricultural product]. *Let's now assume we are in an average household in your woreda. By moving the coffee beans, can you please show me how much of the harvest stays in the household and how much is sold on the local (kebele) market or is exchanged between households (what percentage)? How much of the proportion sold at the local market then goes on to the district market? Which share then goes to the central market? How much is sold to the global market?"* [allocate coffee beans to different scales, guide by follow-up questions if needed]
- *"Now think about the following four kebeles:* [see last pages in this document]. *Would any of the flows be different in these kebeles than for the average household?* "[If so, ask expert to repeat exercise for kebeles where flows are different, with a new set of coffee beans.]
- [When the exercise is complete, take a photo and write down results (…). If a person does not answer to some parts, leave blank. If the flows are the same for a specific kebele as for the woreda indicate with a " –".]

[Repeat exercise for all other agricultural products that the expert knows about.]

Methods: definition of variables

R packages

The following R packages were used, in addition to those already indicted in the main text:

- tidyverse (v1.3.1; Wickham et al. 2019)
- readxl (v1.3.1; Wickham and Bryan 2019)
- factoextra (v1.0.7; Kassambara and Mundt 2020)
- ggpubr (v0.4.0; Kassambara 2020)
- FactoMineR (v2.4; Lê et al. 2008)
- rstatix (v0.7.0; Kassambara 2021)
- PerformanceAnalytics (v2.0.4; Peterson and Carl 2020)
- sjPlot (v2.8.10; Lüdecke 2021)

Main variables

We measured the degree of specialization/comparative advantage for each kebele through Simpson's index based on kebele production/productivity data (gini.simpson.C in R package diverse, v0.1.5, Guevara et al. 2016). Using an index - compared to other approaches to quantifying multifunctionality or diversity such as the threshold approach, averaging approach, or calculating the sum of all ecosystem services (for more information see Hölting et al. 2019a) - allows to evaluate whether ecosystem services are supplied equally of if few are dominant, without making normative choices about thresholds or assuming substitutability of ecosystem services (Hölting et al. 2019b, Hölting et al. 2019a). We chose Simpson's index for infinite samples instead of other diversity indices to measure concentration of both ecosystem service production and productivity, because it is a very meaningful and robust diversity measure and provides good estimates at relatively small sample sizes (Magurran 2011), it reflects best the nature of our data, and it has been widely used in the literature on ecosystem service multifunctionality (Raudsepp-Hearne et al. 2010, Brandt et al. 2014, Stürck and Verburg 2017, Hölting et al. 2019b, Hölting et al. 2020).

We measured the degree of telecoupling for each kebele by a combination of data on average ecosystem service flows to different spatial scales, and ecosystem service production data for each kebele. We calculated the average number of coffee beans attributed by the experts to each spatial scale for each ecosystem service (see bar chart), and weighted the different spatial scales by their degree of telecoupling (from 0 for the household level up to 4 for the global level) to obtain a telecoupling score for each ecosystem service. We then multiplied this score by total annual production for each ecosystem service and summed across ecosystem services to obtain a telecoupling score for each kebele.

Additional variables

Altitude: Mean altitude was calculated from ASTER digital elevation model with 30m resolution (obtained from https://reverb.echo.nasa.gov/; NASA/METI/AIST/Japan Spacesystems and U.S./Japan ASTER Science Team 2009, Duguma et al. 2022).

Forest share: The extent of 12 biophysically distinct land use and land cover (LULC) classes in each kebele was developed from supervised image classification based on imagery and ground control points (for forest, woody vegetation, arable land, pasture, cultivated wetland, grazed wetland, settlement, towns) as well as informed assumptions (for coffee plantations, eucalyptus plantations,

khat, and fruits and vegetables; Duguma et al. 2022). Forest area was then divided by total kebele area (in ha) to obtain forest share.

Landscape diversity: Based on absolute area (in ha) of the 12 LULC classes, we calculated Simpson's diversity index (gini.simpson in R package diverse; see Guevara et al. 2016).

Remoteness: We summed the distance from the nearest town and the distance from the nearest road (both robust scaled, see Duguma et al. 2022).

Share of women in the population: Population data were obtained from Central Statistical Agency (CSA) 2007. We divided the number of women by the total population in each kebele.

Population density: We divided total population divided by total kebele area.

Wealth: Number of tin roofs (identified from satellite imagery) divided by number of households (see Duguma et al. 2022).

Methods: Data analysis

Hierarchical clustering: dendrogram

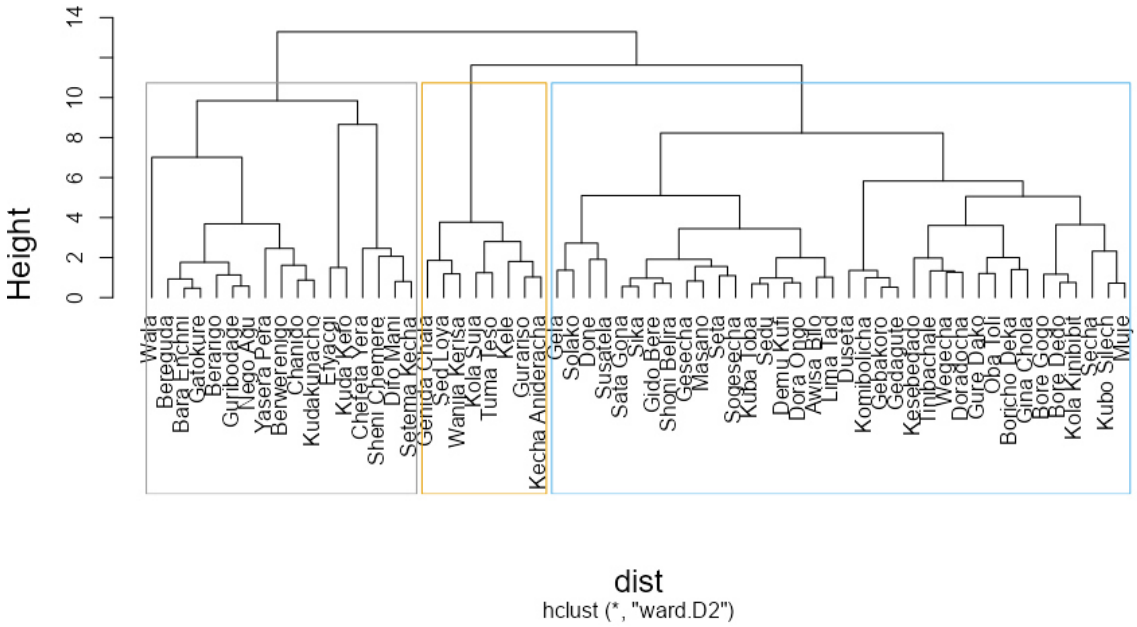

Figure A1.1. Dendrogram of hierarchical clustering analysis of ecosystem service production data for eight ecosystem services in 61 kebeles (smallest administrative units in Ethiopia). The three groups were derived from visual inspection, considering group interpretability.

Linear model: data exploration and transformation

We checked for outliers in and relationships between the dependent and independent variables, normality and zero trouble in the dependent variable, and collinearity between the independent variables (Zuur et al. 2010). We centered and scaled all independent variables. We applied a Box-Cox transformation to the dependent variable, and Yeo-Johnson transformations to telecoupling, comparative advantage, female population, landscape diversity and remoteness to account for non-linearity, non-normality, and heterogeneity in the data. We excluded forest share due to collinearity issues with altitude and landscape diversity.

Linear model: two-way interactions

Based on theoretical considerations, we include two-way interactions between altitude, landscape diversity and comparative advantage. The hierarchical clustering analysis has shown that clusters differ in altitude and in the relationship between specialization and comparative advantage. Kebeles in higher altitudes have lower forest share (one reason is forest clearing in altitude ranges that are unsuitable for coffee; Hylander et al. 2013). Forest share in turn might directly influence comparative advantage (the higher the forest share, the higher the incentive to intensify production of non-forest ecosystem services), but also is also connected to landscape (land use and land cover) diversity, which in turn probably provides more or less incentives for people to specialize in specific ecosystem services or intensify their production (increase productivity) for certain ecosystem services.

Robustness checks: different versions of main variables

To check the robustness of our correlation analyses and the linear model, we computed different versions of our main variables. For telecoupling, we wanted to make sure that our results were not dependent on our weighting of the spatial scales (0 for the household level up to 4 for global), which was chosen somewhat arbitrarily. We calculated one version where we weighted the household level with 1 up to the global level with 5, and another version where we weighted the household and local level with 0 and all the three remaining levels with 1.

For specialization and comparative advantage, which we have calculated by Simpson`s index (infinite version), we additionally calculated the finite version of the Simpson's index (simpson.D in R package diverse), the Shannon index (entropy in R package diverse), and the Gini index (R package ineq, v0.2-13, Zeileis 2014). Note that Shannon index has a reverse interpretation from our other indices: higher values mean more diversity, whereas for Simpson and Gini higher values mean less diversity and more concentration.

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Appendix 2: Results and discussion

Results

Correlation between comparative advantage and specialization (with and without outlier)

The relationship between comparative advantage and specialization remains positive and significant even when excluding the outlier (kebele Genida Chala).

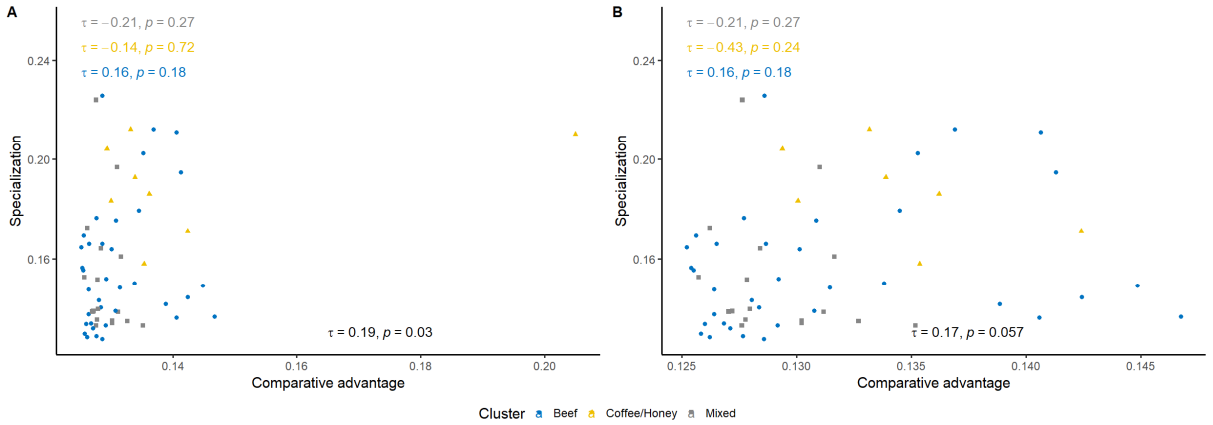

Figure A2.1. Scatterplot of the relationship between comparative advantage and ecosystem service specialization, colored by clusters "beef", "coffee/honey" and "mixed", across all 61 kebeles (A) and excluding the outlier Genida Chala (B). Specialization was measured by Simpson's index based on ecosystem service production data, and telecoupling by a combination of ecosystem service production data and weighted average ecosystem service flow data.

Altitude, forest share and ecosystem services in kebele faming clusters

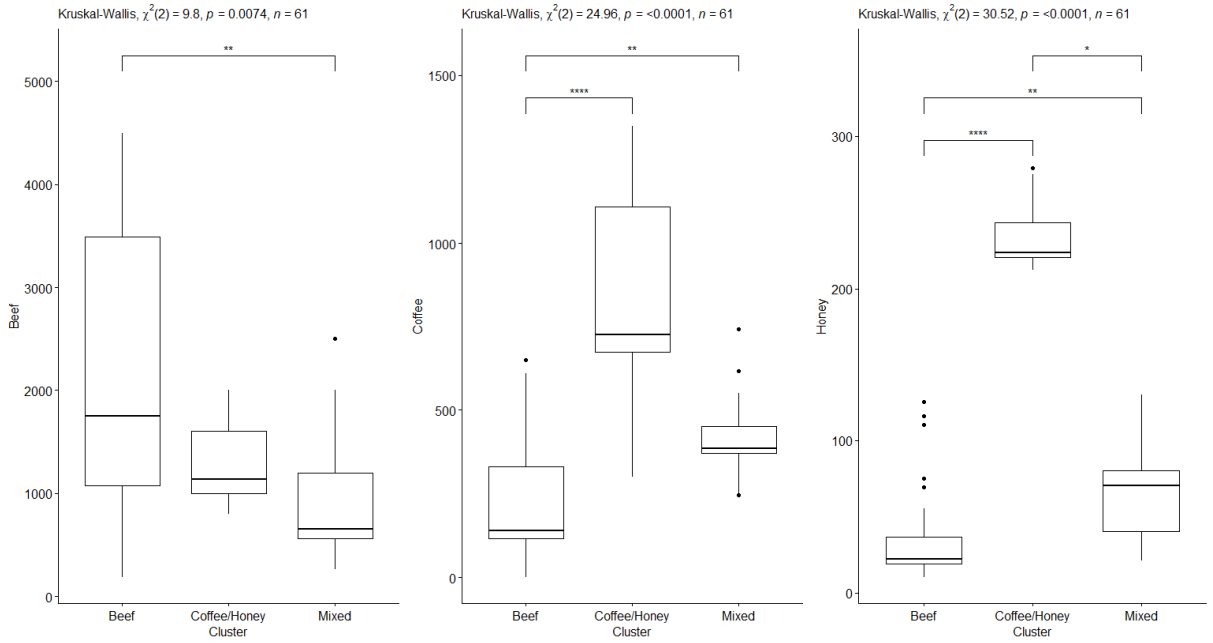

Figure A2.2. Boxplots for beef, coffee and honey production, comparing the three kebele farming type clusters. Kruskal-Wallis test for comparing more than two groups for non-parametric data, Dunn's test for multiple pairwise comparison between groups with Bonferroni correction.

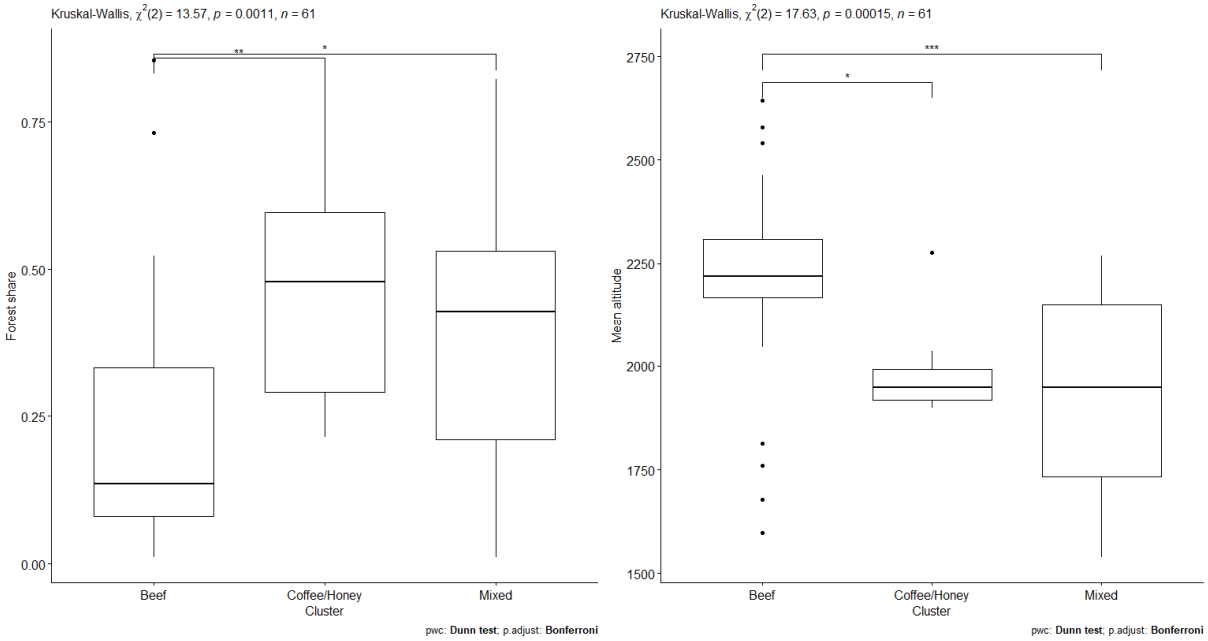

Figure A2.3. Boxplots for forest share and altitude, comparing the three kebele farming type clusters. Kruskal-Wallis test for comparing more than two groups for non-parametric data, Dunn's test for multiple pairwise comparison between groups with Bonferroni correction.

Robustness checks: correlations

The relationship between telecoupling and specialization across all kebeles is robust against the different versions of our main variables. The relationship is also robust in the kebele farming type clusters: for the "beef" and the "mixed" cluster, the relationship remains positive and significant at least at the 10% level, and the evidence for the "coffee/honey" cluster remains inconclusive, except for the finite Simpson's index.

The relationship between comparative advantage and specialization across all kebeles is robust against the different versions of the variables. For the relationship between comparative advantage and specialization in the clusters, the evidence remains similarly inconclusive for all different versions of the variables.

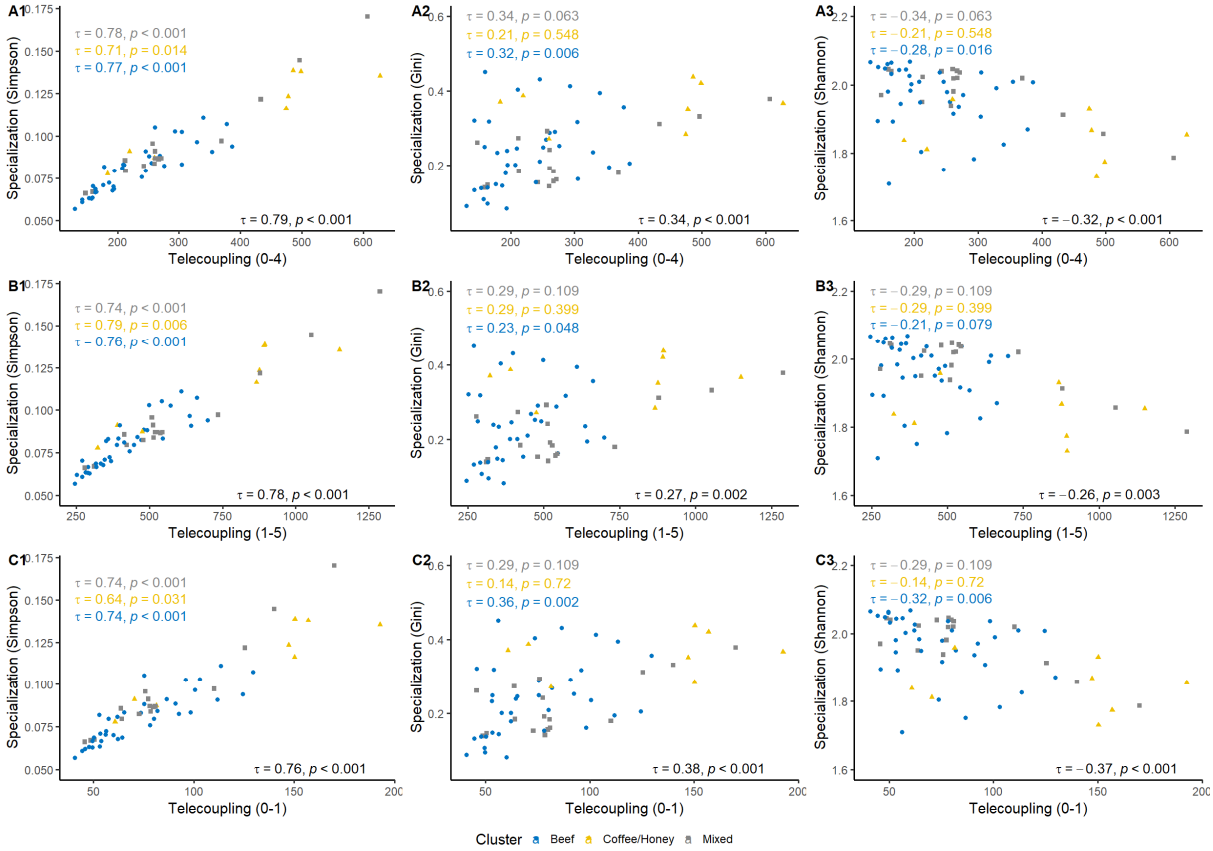

Figure A2.4. Scatterplot of relationship between telecoupling and ecosystem service specialization across 61 kebeles, colored by clusters "beef", "coffee/honey" and "mixed". For telecoupling: weighting was 0 for the household level up to 4 for the global level (A); 1 for the household level, up to 5 for the global level (B); 0 for the household and local level and 1 for the three remaining levels (C). Specialization measured by Simpson's index (finite, 1), Gini index (2), and Shannon index (3).

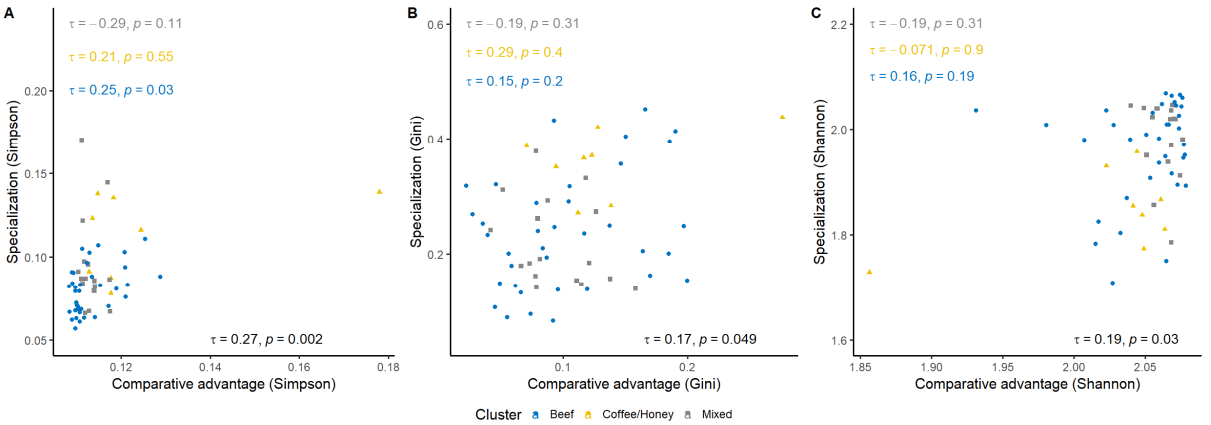

Figure A2.5. Scatterplot of relationship between comparative advantage and ecosystem service specialization across 61 kebeles, colored by clusters "beef", "coffee/honey" and "mixed". Specialization and comparative advantage measured by Simpson's index (finite, A), Gini index (B), and Shannon index (C).

Robustness checks: linear model

The main results of the linear model (positive significant coefficients for telecoupling and the interaction between comparative advantage and altitude) are robust against different versions of our main variables (Table A2.1, A2.3 and A2.4), except for the finite version of the Simpson's index (Table A2.2), which results in a model where the influence of telecoupling on specialization compared to the other variables is extremely high.

Table A2.1. Results of the linear model testing the influence of social and ecological kebele characteristics on the degree of ecosystem service specialization in a kebele. All predictor terms are continuous. Specialization measured by ***Simpson's index (infinite version)*** *based on ecosystem service production data. Telecoupling measured by a combination of ecosystem service production data and weighted average ecosystem service flow data. For Telecoupling, the weighting was 0 for the household level, up to 4 for the global level. For Telecoupling_2, the weighting was 1 for the household level, up to 5 for the global level. For Telecoupling_3, the weighting was 0 for the household and local level and 1 for the three remaining levels. Models selected by stepwise backward model selection based on the Akaike information criterion (AIC).*

	Specialization								
Term	*Coeff.*	*Std. error*	*P-value*	*Coeff.*	*Std. error*	*P-value*	*Coeff.*	*Std. error*	*P-value*
Intercept	-0.01	0.10	0.931	-0.01	0.11	0.927	-0.01	0.10	0.938
Comparative advantage	0.19	0.13	0.159	0.25 *	0.13	0.070	0.15	0.13	0.263
Telecoupling	0.66 ***	0.15	<0.001						
Mean altitude	0.21 *	0.12	0.083	0.27 **	0.13	0.046	0.17	0.11	0.134
Population density	-0.35 **	0.14	0.018	-0.24	0.15	0.126	-0.36 ***	0.14	0.010
Wealth	-0.25 **	0.11	0.026	-0.25 **	0.11	0.030	-0.23 **	0.10	0.031
Comparative advantage*Mean altitude	0.33 *	0.18	0.065	0.36 *	0.18	0.051	0.29 *	0.17	0.099
Telecoupling_2				0.52 ***	0.16	0.002			
Female population				-0.20	0.12	0.109			
Telecoupling_3							0.71 ***	0.14	<0.001
Observations	61			61			61		
R^2 / R^2 adjusted	0.398 / 0.331			0.370 / 0.286			0.437 / 0.375		

** p<0.1 ** p<0.05 *** p<0.01*

Table A2.2. Results of the linear model testing the influence of social and ecological kebele characteristics on the degree of ecosystem service specialization in a kebele. All predictor terms are continuous. Specialization measured by ***Simpson's index (finite version)*** *based on ecosystem service production data. Telecoupling measured by a combination of ecosystem service production data and weighted average ecosystem service flow data. For Telecoupling, the weighting was 0 for the household level, up to 4 for the global level. For Telecoupling_2, the weighting was 1 for the household level, up to 5 for the global level. For Telecoupling_3, the weighting was 0 for the household and local level and 1 for the three remaining levels. Models selected by stepwise backward model selection based on the Akaike information criterion (AIC).*

	Specialization								
Term	*Coeff.*	*Std. error*	*P-value*	*Coeff.*	*Std. error*	*P-value*	*Coeff.*	*Std. error*	*P-value*
Intercept	0.00	0.04	1.000	0.00	0.04	1.000	-0.00	0.04	1.000
Telecoupling	1.00 ***	0.05	<0.001						
Population density	-0.10 **	0.05	0.035	-0.13 **	0.05	0.015			
Telecoupling_2				1.06 ***	0.06	<0.001			
Mean altitude				0.07	0.05	0.172	-0.13 ***	0.04	0.004
Wealth				-0.09 **	0.04	0.035			
Landscape diversity				-0.06	0.04	0.163			
Telecoupling_3							0.92 ***	0.04	<0.001
Observations	61			61			61		
R^2 / R^2 adjusted	0.909 / 0.906			0.913 / 0.905			0.887 / 0.883		
							** p<0.1*	*** p<0.05*	**** p<0.01*

Table A2.3. Results of the linear model testing the influence of social and ecological kebele characteristics on the degree of ecosystem service specialization in a kebele. All predictor terms are continuous. Specialization measured by ***Gini index*** *based on ecosystem service production data. Telecoupling measured by a combination of ecosystem service production data and weighted average ecosystem service flow data. For Telecoupling, the weighting was 0 for the household level, up to 4 for the global level. For Telecoupling_2, the weighting was 1 for the household level, up to 5 for the global level. For Telecoupling_3, the weighting was 0 for the household and local level and 1 for the three remaining levels. Models selected by stepwise backward model selection based on the Akaike information criterion (AIC).*

	Specialization								
Term	*Coeff.*	*Std. error*	*P-value*	*Coeff.*	*Std. error*	*P-value*	*Coeff.*	*Std. error*	*P-value*
Intercept	-0.07	0.10	0.478	-0.08	0.10	0.453	-0.06	0.10	0.531
Comparative advantage	0.13	0.10	0.219	0.15	0.11	0.162	0.09	0.10	0.382
Telecoupling	0.64 ***	0.14	<0.001						
Mean altitude	0.24 *	0.12	0.059	0.28 **	0.13	0.040	0.15	0.11	0.201
Landscape diversity	-0.04	0.11	0.709	-0.02	0.12	0.852	-0.09	0.11	0.392
Female population	-0.17	0.12	0.142	-0.22 *	0.12	0.069			
Population density	-0.34 **	0.13	0.015	-0.31 **	0.14	0.035	-0.40 ***	0.12	0.002
Wealth	-0.17 *	0.10	0.100	-0.18	0.11	0.103	-0.15	0.10	0.121
Comparative advantage*Mean altitude	0.30 ***	0.11	0.010	0.32 ***	0.11	0.007	0.26 **	0.11	0.021
Comparative advantage*Landscape diversity	0.22 **	0.10	0.039	0.25 **	0.11	0.024	0.19 *	0.10	0.069
Telecoupling_2				0.57 ***	0.15	<0.001			
Telecoupling_3							0.75 ***	0.13	<0.001
Observations	61			61			61		
R^2 / R^2 adjusted	0.527 / 0.444			0.483 / 0.392			0.544 / 0.474		

** p<0.1 ** p<0.05 *** p<0.01*

Table A2.4. Results of the linear model testing the influence of social and ecological kebele characteristics on the degree of ecosystem service specialization in a kebele. All predictor terms are continuous. Specialization measured by ***Shannon index*** *based on ecosystem service production data. Telecoupling measured by a combination of ecosystem service production data and weighted average ecosystem service flow data. For Telecoupling, the weighting was 0 for the household level, up to 4 for the global level. For Telecoupling_2, the weighting was 1 for the household level, up to 5 for the global level. For Telecoupling_3, the weighting was 0 for the household and local level and 1 for the three remaining levels. Models selected by stepwise backward model selection based on the Akaike information criterion (AIC).*

	Specialization								
Term	*Coeff.*	*Std. error*	*P-value*	*Coeff.*	*Std. error*	*P-value*	*Coeff.*	*Std. error*	*P-value*
Intercept	0.03	0.10	0.779	0.03	0.11	0.773	0.02	0.10	0.828
Comparative advantage	0.22 *	0.12	0.067	0.26 **	0.12	0.035	0.16	0.11	0.160
Telecoupling	-0.52 ***	0.15	0.001						
Mean altitude	-0.33 **	0.12	0.012	-0.35 **	0.13	0.012	-0.24 **	0.11	0.038
Remoteness	0.17	0.13	0.179	0.19	0.13	0.151			
Female population	0.21 *	0.12	0.084	0.26 **	0.12	0.039	0.16	0.12	0.173
Population density	0.37 **	0.15	0.017	0.32 **	0.16	0.046	0.34 **	0.14	0.017
Wealth	0.29 ***	0.11	0.010	0.29 **	0.11	0.012	0.26 **	0.10	0.015
Comparative advantage*Mean altitude	0.35 **	0.16	0.030	0.37 **	0.16	0.026	0.26 *	0.15	0.080
Telecoupling_2				-0.43 **	0.16	0.011			
Telecoupling_3							-0.62 ***	0.14	<0.001
Observations	61			61			61		
R^2 / R^2 adjusted	0.447 / 0.362			0.405 / 0.313			0.463 / 0.392		

** p<0.1 ** p<0.05 *** p<0.01*

Including dummy variables for imputed values in the model showed that imputed coffee values had a significant influence on the model results. However, we are relatively confident in our assumption that these kebeles do not produce any coffee, since they lie outside the coffee growing zone. A high influence on the model results by these values was expected, because none of the other ecosystem services were reported as "zero". This means that zero coffee production has a high influence on telecoupling, specialization and comparative advantage for these kebeles. The remaining imputed values (for eucalyptus and sorghum) did not show a significant influence on the model results.

Table A2.5. Results of the full linear model testing the influence of social and ecological kebele characteristics on the degree of ecosystem service specialization in a kebele. "coffee_impute" is a dummy variable for all kebeles where coffee data were imputed, "other_impute" for any other imputed ecosystem services.

	Specialization		
Term	*Coefficient*	*Standard error*	*P-value*
Intercept	-0.20 *	0.12	0.095
Comparative advantage	-0.04	0.14	0.809
Telecoupling	0.72 ***	0.17	<0.001
Mean altitude	0.05	0.15	0.717
Landscape diversity	-0.04	0.12	0.772
Remoteness	-0.05	0.12	0.677
Female populaton	-0.06	0.12	0.589
Population density	-0.44 ***	0.15	0.004
Wealth	-0.11	0.11	0.319
Coffee_impute	1.77 ***	0.46	<0.001
Other_impute	-0.01	0.36	0.980
Comparative advantage*Mean altitude	0.13	0.21	0.552
Mean altitude*Landscape diversity	0.07	0.15	0.619
Comparative advantage*Landscape diversity	0.26	0.24	0.281
Observations	61		
R^2 / R^2 adjusted	0.584 / 0.469		
	** p<0.1*	*** p<0.05*	**** p<0.01*

Telecoupling and comparative advantage as significant predictors

By comparing our model with a model without comparative advantage and telecoupling, we can be confident that telecoupling and comparative advantage both significantly contribute to predictions of specialization (ANOVA; $F(4, 49) = 6.7232$, $p < 0.001$).

We are confident that telecoupling and comparative advantage both contribute to predictions of specialization (comparative advantage in its interaction with altitude): they have significant coefficients in the full model; their removal from the full model reduces model fit (see ANOVA results); and they are significant when fit by themselves. We additionally used the dredge function starting from the full model (R package MuMIn, v1.43.17; Barton 2020) to check if telecoupling and comparative advantage are part of the best models (according to AIC). All of the best ranked models included telecoupling, it was the most important predictor, it had the strongest effect, and was the most significant of all the predictors. Some of the best models included comparative advantage and its interaction with altitude, it was fifth important predictor, and the interaction with altitude had a significant positive effect on average.

Discussion

Correlations between ecosystem services production and productivity

For all ecosystem services, production and productivity are positively significantly correlated, except for beef, coffee and teff. The productivity data for beef were derived from cattle data and not directly collected, which might explain the divergent finding here. Cultural reasons might explain the missing relationship for coffee and teff (see manuscript).

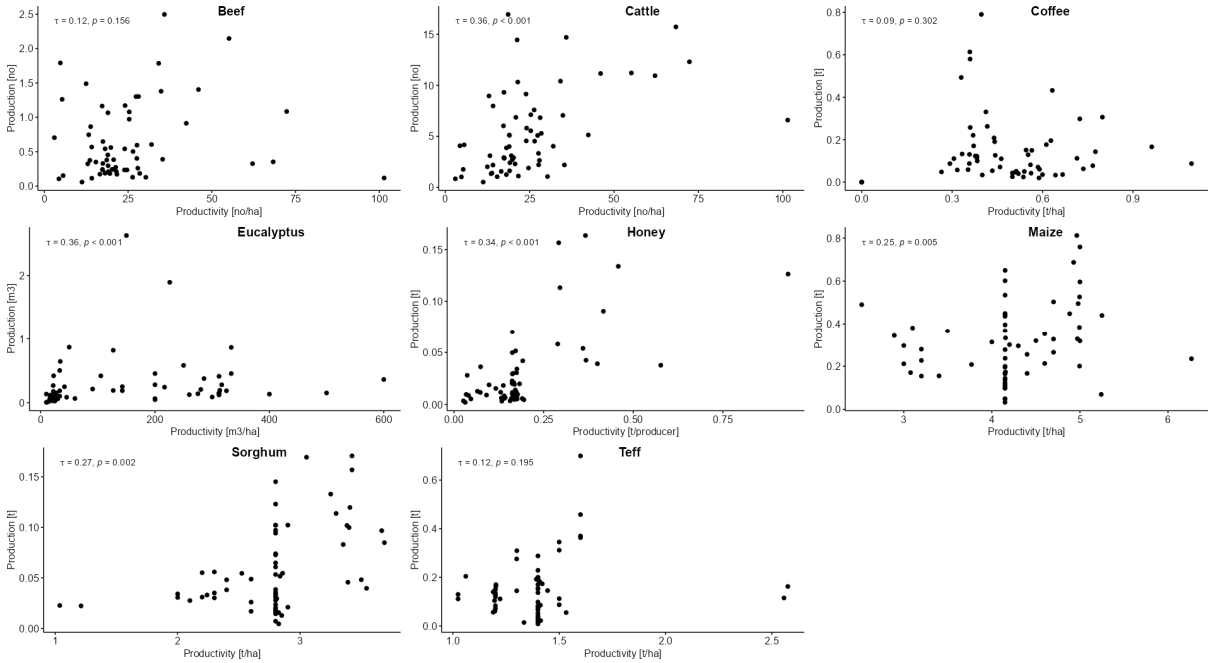

Figure A2.6. Correlations (Kendall's Tau coefficient) between ecosystem service production (adjusted for kebele area) and productivity for 61 kebeles.

Chapter IV: Plural valuation in southwestern Ethiopia: Disaggregated ecosystem service values in a smallholder landscape

Maria Brück, Jannik Schultner, Birhanu B. Negash, Dadi F. Damu, David J. Abson

Major revisions with People and Nature

Plural valuation in southwestern Ethiopia: Disaggregated ecosystem service values in a smallholder landscape

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Abstract

1. Recognizing diversity in preferences and ascribed values for ecosystem services in decision-making can help to realize more sustainable and equitable policies for transformative change.
2. The goal of this paper was to assess how rankings of ecosystem services (i.e. their relative importance in people's lives) relate to people's individual characteristics, their social-ecological context, and the values they ascribe to each ecosystem service.
3. In our case study in southwestern Ethiopia, we considered 11 ecosystem services and four value types (direct use, exchange, relational, intrinsic). We used descriptive statistics, hierarchical clustering, and chi-square tests of independence to analyze the data.
4. On average, maize and teff were ranked as most important, and direct use and relational value were the most important value types. Beneficiaries often ascribed multiple values to each ecosystem service, and direct use and relational values better explained overall importance rankings than exchange or intrinsic values.
5. Five groups of beneficiaries, who each prioritized a different set of ecosystem services, differed in their occupation, and in their social-ecological context, in terms of the villages they lived in and the ecosystem services they produced. Beneficiaries in each of the five groups ascribed different value types to their prioritized ecosystem services, and these did not always align with the value types that were generally judged most important by the group.
6. We recommend that sustainable landscape management should take into account the diversity of people's ecosystem service rankings and values, including non-exchange values.

Key words: disaggregation, ecosystem services, Ethiopia, plural valuation, smallholder landscape, socio-cultural values

1. Introduction

Recognizing the multiple values associated with human-nature interactions can help generate more equitable and sustainable actions for transformative change (Beery, Quaas, & Stenseke, 2021; IPBES, 2022; Zafra-Calvo et al., 2020). There are multiple conceptual frameworks for describing, categorizing and valuing those human-nature interactions, e.g. ecosystem services (ES, Millennium Ecosystem Assessment, 2005), nature's contributions to people (NCP, Díaz et al., 2018), or human-environment systems (Scholz & Binder, 2003), each with their own strengths and weaknesses. For conceptual clarity, we chose to frame such human-nature interactions in terms of ES (defined here as the benefits obtained by humans from their interactions with ecological structures and functions, Millennium Ecosystem Assessment, 2005) as a widely used and understood approach in both science and practice.

During assessments of ES, relevant insights are often lost when aggregating data across groups of people (Arias-Arévalo, Gómez-Baggethun, Martín-López, & Pérez-Rincón, 2018; Brück, Abson, Fischer, & Schultner, 2022; Spangenberg & Settele, 2010). Among others, the relative importance of ES can differ between women and men (Coelho-Junior et al., 2021; Lau, Hicks, Gurney, & Cinner, 2019; Oteros-Rozas et al., 2014), wealth groups (Lau, Hicks, Gurney, & Cinner, 2018; Tadesse, Zavaleta, Shennan, & Fitzsimmons, 2014), urban and rural populations (Arias-Arévalo, Martín-López, & Gómez-Baggethun, 2017; Lapointe, Gurney, & Cumming, 2020; Martín-López et al., 2012), and between different types of occupation (Brooks, Smith, Holland, Poppy, & Eigenbrod, 2014; Hicks, Graham, & Cinner, 2013; Horcea-Milcu, Leventon, Hanspach, & Fischer, 2016). The relative importance of ES to people's livelihoods can also be shaped by their social-ecological context, for example by people's main livelihood or productive activities, or their local surroundings (Oteros-Rozas et al., 2014; Reyes-Arroyo, Camacho-Valdez, Saenz-Arroyo, & Infante-Mata, 2021; Tauro, Gómez-Baggethun, García-Frapolli, Lazos Chavero, & Balvanera, 2018). For equity concerns, it is therefore important that ES assessments are disaggregated by beneficiary groups (Brück et al., 2022).

Similarly, valuations of ES that aggregate across value types, focus solely on monetary or exchange values, or subsume plural values into one commensurable metric are problematic for understanding the complex way values are ascribed to ES (Arias-Arévalo et al., 2018; Spangenberg & Settele, 2010). For example, monetary values often do not reflect well the actual relative importance of ES in people's lives (Brooks et al., 2014; Martín-López, Gómez-Baggethun, García-Llorente, & Montes, 2014; Tadesse et al., 2014). Instead, people hold a plurality of values, and instrumental values are sometimes considered less important than other value types (Arias-Arévalo et al., 2017; Elbakidze et al., 2021; Gale & Ednie, 2020; Topp, Loos, & Martín-López, 2021), such as relational values (the preferences, principles, and virtues associated with relationships, both interpersonal and as articulated by policies and social norms; Chan et al., 2016; Chan, Gould, & Pascual, 2018).

Here we assume that each ES may provide multiple benefits and be valued for a range of different reasons (Chan, Satterfield, & Goldstein, 2012; also termed "bundled" values or benefits; Hoehn, Lupi, & Kaplowitz, 2003; Klain, Satterfield, & Chan, 2014). For example, an ethnographic study in Ethiopia showed that coffee has numerous sociocultural benefits in addition to being an important exchange commodity, such as being a medium for conflict resolutions and a local traditional medicine (Bulitta & Duguma, 2021). Thus, people may ascribe a range of values, including instrumental, relational and intrinsic values, to coffee. Even in monetary valuation approaches, such as discrete choice experiments, that acknowledge the bundled values associated with ES, the use of a single commensurable metric (exchange value) for ES valuation is problematic, because it is based on the implicit assumption that the different sorts of values ascribed to ES are substitutable (Arias-Arévalo et al., 2018; Spangenberg & Settele, 2010). Here, we assume that those multiple ascribed values are non-substitutable and need to be valued individually, assessing not just the 'strength' of those values, but also how they relate to each other and to overall value ascription for a given ES (Chan et al., 2016; Pascual et al., 2017). Therefore, ES valuation approaches that acknowledge and elicit

plural value ascription (disaggregation by value type) are also crucially important. In the absence of such pluralistic, disaggregated assessments it is possible ES will be optimized for a single type of value (such as exchange value) at the 'system' level, at the expense of other important values associated with those ES, and the equitable distribution of the benefits ascribed to those ES. A disaggregated perspective can, therefore, provide crucial insights regarding the plurality of values and beneficiaries associated with ES provision and appropriation (Brück et al., 2022).

Different research approaches that capture this plurality facilitate the assessment of relative importance of ES and the values ascribed to nature from a disaggregated perspective, including comparisons between different beneficiary groups and value types (Arias-Arévalo et al., 2018; Zafra-Calvo et al., 2020). The relative importance of ES can be assessed, for example, through ranking exercises, Likert scale ratings, Q sorts, or the distribution of counters (Hartel et al., 2014; Hicks, Cinner, Stoeckl, & McClanahan, 2015; Maniatakou, Berg, Maneas, & Daw, 2020; Tauro et al., 2018). Values ascribed to nature can be elicited and disaggregated through qualitative (e.g. narrative approaches, interviews, participant observation; Arias-Arévalo et al., 2017; Coelho-Junior et al., 2021; Elbakidze et al., 2021; Topp et al., 2021) or quantitative approaches (e.g. rating value statements, Q methodology; Gale & Ednie, 2020; Inglis, Pascual, & Castro, 2021; Klain, Olmsted, Chan, & Satterfield, 2017; Riechers, Balázsi, Engler, Shumi, & Fischer, 2021; Winter & Lockwood, 2004). A range of case studies have already qualitatively investigated why (for which reasons or values) ES or nature matter to people (Arias-Arévalo et al., 2017; Lau et al., 2019; Maniatakou et al., 2020; Tauro et al., 2018), but quantitative investigations remain scarce. With regard to quantitative approaches, disentangling the relationship between the relative importance of ES and the specific values ascribed to those services can deliver additional important information on the reasons why people prioritize certain ES (Schutter, Hicks, Phelps, & Belmont, 2021).

In this paper, we seek to assess not only the relative importance of ES, or the different value types ascribed to nature in general, but we quantitively explore the relationship between ES rankings and individual value ascription. Assessing the diversity of values ascribed to ES supports a more holistic understanding of the importance of ES, by understanding the reasons for which ES are valued, and also how well values ascribed to ES are reflected in rankings of general importance.

The goal of this paper is to assess how rankings of ES (according to their general importance in people's lives) relate to people's individual characteristics, their social-ecological context, and the types of values they ascribe to each ES. Through a case study in southwestern Ethiopia, we address the following aims:

(1) To assess, in general, the relative importance that people ascribe to different ES and to different value types
(2) To assess, more specifically, the value types people ascribe to each ES, and how they relate to the relative importance of ES
(3) To assess the influence of individual characteristics and contexts on the relative importance of ES, by identifying main groups of beneficiaries based on their ES rankings, and by assessing differences in their individual characteristics, including gender, wealth, and occupation, and in their social-ecological context, including geographical location and ES production and consumption.

2. Methods

2.1 Study area

The study area consisted of three woredas (districts), in Jimma Zone, Oromia Region, Ethiopia, namely Gera, Gumay and Setema woreda (Fig. 1). The landscape is characterized by a mosaic of farmland and moist evergreen Afromontane forest (Hylander, Nemomissa, Delrue, & Enkosa, 2013) and is a recognized biodiversity hotspot (Mittermeier, Turner, Larsen, Brooks, & Gascon, 2011). Local smallholders are especially dependent on nature, and ES are locally important for subsistence and income generation (Schultner et al., 2021; Shumi et al., 2019), but also provide benefits of global importance, such as carbon storage (Beenhouwer et al., 2016). The landscape is undergoing rapid social-ecological change due to different social, demographic, economic, environmental, technological, political and governance drivers, such as population growth, land use change and climate change (Jiren, Hanspach, et al., 2020). In this context, it is important to understand which ES are important to local people and why, in order to inform decision-making for sustainable land management.

2.2 Data collection

In November and December 2021, we collected data on the relative importance of ES and the values ascribed to them in eight kebeles (smallest administrative units in Ethiopia) and one town through a questionnaire. To investigate the role of social-ecological context, kebeles in our study area were clustered into four social-ecological groups, based on a range of ecological and social variables, including land use and land cover data, altitude, remoteness, and wealth. The pasture-cropland, the khat-cropland, the woody vegetation and the accessible-wealthy group were characterized, respectively, by high availability of pasture and arable land, by high availability of khat (a popular plant stimulant) and arable land, by high extent of woody vegetation cover, and by being relatively accessible and wealthy (Duguma, Schultner, Abson, & Fischer, 2022). Out of the 78 kebeles in our study area, we then selected eight kebeles – two from each social-ecological group (Fig. 1, Table A1). For practical reasons, they were also chosen based on their accessibility due to geographical and security issues. We additionally selected one district town (Toba town) in Gumay woreda, which also belongs to the accessible-wealthy group, to reflect non-farmers in the sample.

Data were collected in the eight kebeles and the town for six days each, applying stratified sampling to achieve equally sized groups of women and men, and convenience sampling within each stratum, where respondents were approached randomly. We obtained informed consent from each participant, which was obtained verbally to overcome barriers related to illiteracy and anonymity. A final sample of 316 participants answered questions regarding the relative importance of ES, whereas only a sub-sample of 164 participants answered additional questions regarding values due to time restrictions. The full sample of 316 participants remained below the threshold of 385 required participants for a representative sample (study area population of roughly 270,000 people, 95% confidence level, 5% margin of error), due to resource constraints and security issues. However, the final sample represented the study area's population relatively well in terms of gender and occupation. Approximately 89% of the population in Jimma Zone are smallholder farmers (Jiren, Hanspach, et al., 2020), compared to 89.5% in our sample. Approximately half of the total population in Jimma Zone are women (Central Statistical Agency [CSA], 2007), compared to 46% in our sample.

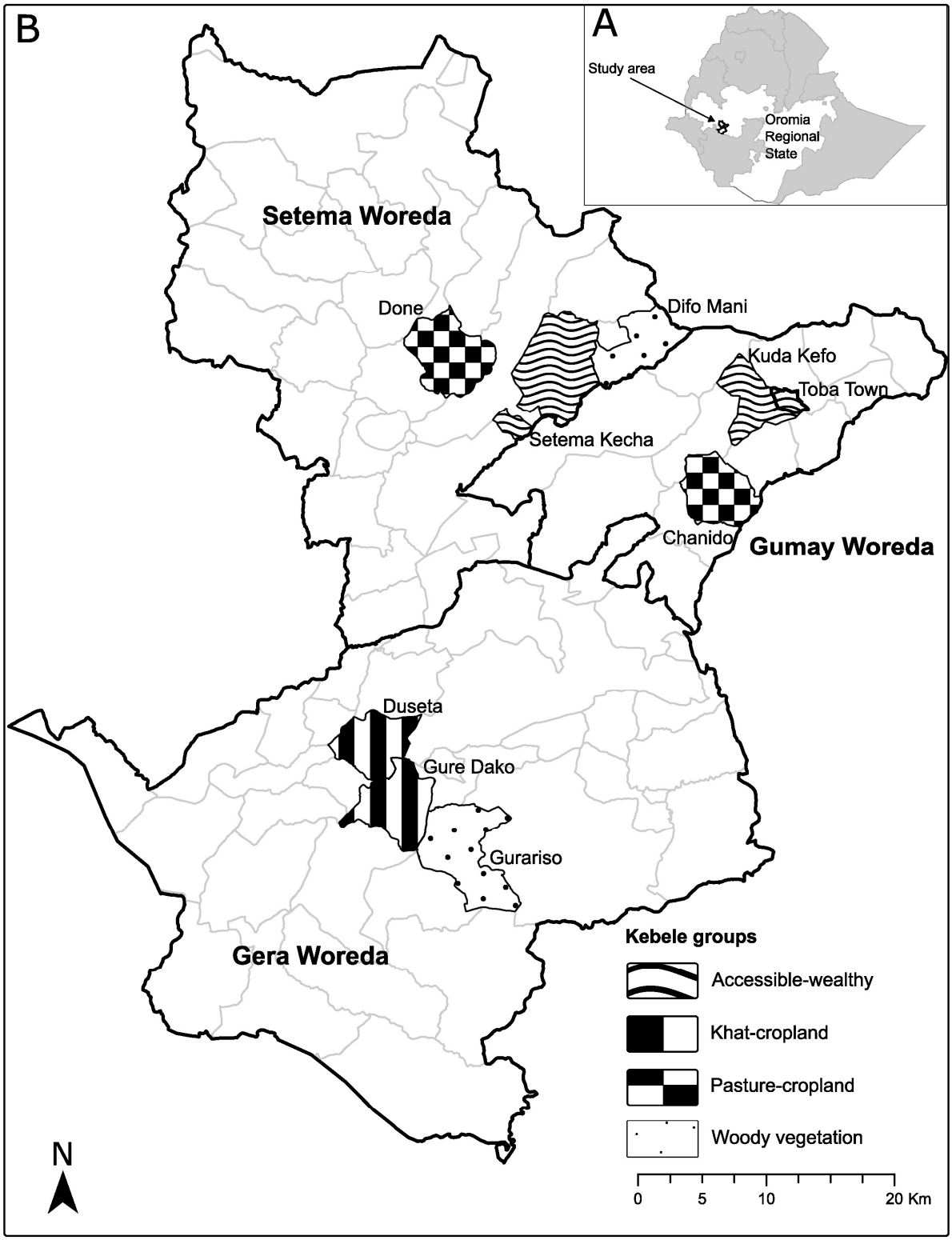

Figure 1. Map of the study area, which is situated in Oromia regional state in Ethiopia (A). Data were collected in eight kebeles (smallest administrative units in Ethiopia) and one town in three different woredas (districts) (B). Each kebele belongs to one of four social-ecological kebele groups (see section 2.2).

We selected 11 ES, namely beef, biodiversity, cattle, coffee, eucalyptus, firewood, honey, khat, maize, sorghum and teff, to be included in our questionnaire. We chose these ES, because, from previous research in the study area, we knew that these services were important to the local people. Households usually own a small number of livestock, and cattle are used as draft animals and also considered a valuable capital asset (Manlosa, Schultner, Dorresteijn, & Fischer, 2019). We distinguished between cattle used for general purposes versus cattle used specifically for beef fattening (i.e. for meat production). We also included ES stemming from the use of woody plants, namely eucalyptus (*Eucalyptus spp.*), firewood and honey (Shumi et al., 2019). Coffee (*Coffea arabica*) and khat (*Catha edulis*) are the main cash crops in the study area, whereas maize (*Zea mays*), sorghum (*Sorghum bicolor*) and teff (*Eragrostis tef*) are the main food crops in the study area (Manlosa, Hanspach, Schultner, Dorresteijn, & Fischer, 2019). Biodiversity delivers important local and global benefits (Beenhouwer et al., 2016).

A multitude of frameworks exists for the categorization of values, e.g. the Total Economic Value (TEV) or The Economics of Ecosystems and Biodiversity (TEEB) framework (Jacobs et al., 2018; TEEB – The Economics of Ecosystems and Biodiversity, 2010; Turner et al., 2003). In this paper, we followed the IPBES framework (Pascual et al., 2017), and considered instrumental, relational, and intrinsic values (Chan et al., 2016; Himes & Muraca, 2018). In our case study context, it made sense to differentiate between direct use value (which people obtain from directly consuming an ES) and exchange value (which people obtain from selling or trading ES). Relational values encompass both human-nature relationships and human-human relationships that are mediated by nature (Chan et al., 2016; Chan et al., 2018; Himes & Muraca, 2018), and among the many different types of relational values, we chose to focus on the social aspect of ES production or consumption which brings people together ("social cohesion"). We understood intrinsic value as the value that nature has in and of itself (inherent value), independent of human benefit (Chan et al., 2016). We thus included four value types: exchange, direct use, relational, and intrinsic value (Table 1).

Table 1. Definition of value types as used in this paper, based on Chan et al. (2016) and Pascual et al. (2017).

Value type	**Definition**
Direct use	Instrumental value obtained from directly using or consuming an ES
Exchange	Instrumental value obtained from selling or trading an ES
Relational	Value of the social aspect of ES production or consumption, i.e. "social cohesion"; the human-human relationship mediated by an ES
Intrinsic	Value that an ES has in and of itself (inherent value), independent of human benefit

The questionnaire was translated into the local language Afaan Oromoo and consisted of three parts (see full questionnaire in Appendix). In the first part, participants were asked about their kebele, their gender, wealth (number of cattle, land size and type of housing as potential proxies) and occupation as well as the ES they produced and consumed. The second part was a picture-based ES ranking exercise to assess the general importance of the 11 ES to participants' livelihoods (Fig. 2). Here, participants were asked to rank pictures of the ES based on their general importance to them. Such a picture-based ES ranking, also called ES card game, is a socio-cultural preference assessment method (Harrison et al., 2018; Jacobs et al., 2018), which has already been applied in other studies (Iniesta-Arandia, García-Llorente, Aguilera, Montes, & Martín-López, 2014; Martín-López et al., 2012; Oteros-Rozas et al., 2014; Tauro et al., 2018), and is an efficient and quick way to gather information. The third part of the questionnaire consisted of distributing tokens, to assess the value types ascribed to each ES (Fig. 2). Prompted by one specific question for each value type (e.g. "How important is each natural product or benefit to you because you directly use or consume it?" for direct use value), participants were asked to distribute 30 tokens between the 11 ES for each of the four value types. Participants were allowed to leave some or all tokens undistributed (if

the value type was relatively unimportant to them). This thus resulted in a weighted ranking of the 11 ES for each of the four value types. Inspired by other approaches in the literature that used counters to assess ES importance (Hicks et al., 2015; Lau et al., 2018, 2019), our approach allowed for differentiated comparisons between the different value types.

Ecosystem services ranking (pictures)	**Directly used or consumed**	**Sold or traded**	**Brings people together**	**Simply exists without any benefit**
	30 coffee beans	30 coffee beans	30 coffee beans	30 coffee beans
				
				
				
				
...				

Figure 2. Stylized version of the data sheet used in the questionnaire (for more details see Appendix). In the first column, the participant ranked pictures of the 11 ES by their general importance to their livelihood. Each of the following columns represents one value type (direct use, exchange, relational, intrinsic). For each value type, participants distributed 30 tokens (coffee beans) between the 11 ES, to indicate a weighted ranking of the ES in each value type.

2.3 Data analysis

Data were analyzed using R version 4.1.3 (R Core Team, 2022; main R packages used are indicated in the text, information on additional packages can be found in Appendix). We checked the data for missing values and inconsistencies. If a participant had indicated that an ES was unimportant (and therefore was not included in the picture ranking), we replaced the missing rank by 11 (the lowest possible rank), and assumed that the number of tokens ascribed to the ES was 0 for all value types. If a participant had indicated for one or more ES that they did not want to answer questions related to that ES, we kept the missing values due to lack of information. To ensure consistency of the data, we made some adjustments to the number of tokens where necessary (see data processing in Appendix).

In order to assess the relative importance of ES, we calculated the median rank and interquartile range (IQR) for each ES based on the picture-based ES ranking. Based on the sub-sample of 164 participants, we assessed the relative importance of value types by calculating the mean number of distributed tokens for each of the four value types (more distributed tokens = more importance). To assess the values participants ascribed to individual ES, we calculated the mean number of tokens attributed to each ES in each value type.

To reduce the dimensionality of our disaggregated data, we clustered participants based on their picture-based ES ranking. We applied hierarchical clustering with Kendall distance to account for the ordinal data structure, and Ward clustering method (Dist in R package amap; Lucas, 2019). Here, we excluded 19 observations due to missing information about the rank of one or more ES.

We chose five clusters based on group interpretability and multiple statistical tests, including the Calinski-Harabasz criterion and the Dunn index, which helped to determine the optimal number of clusters and to assess the strength of the clustering structure (Fig. A1). For each of the five beneficiary clusters (which we call beneficiary groups from here on), we calculated the deviation from the overall median rank for each ES. We also calculated the relative importance of each value type and the values participants ascribed to individual ES as well as the respective deviations from the overall sample means.

To assess the relationship between the ES rankings and participants' individual characteristics as well as their social-ecological context, we assessed differences between the beneficiary groups by applying a chi-square test of independence. We evaluated whether there was a significant association between the beneficiary groups and other categorical variables, which described the participants' individual characteristics or their social-ecological context (gender, wealth, occupation, social-ecological kebele group). Where the expected frequency in any cell was smaller than 5, we computed p-values by Monte Carlo simulation with 2,000 replicates. In addition, we calculated Pearson residuals (absolute standardized residuals) for each cell to assess their contribution to the overall chi-square score. Cells with the highest Pearson residuals contribute the most to the total chi-square score, where positive/negative values specify an attraction/repulsion (positive/negative association) between the corresponding row and column variables. We decided to use number of cattle as a measure of wealth, and split the variable at its median to create two groups (number of cattle owned less than 3 = poor; number of cattle owned 3 or more = wealthy; see data processing in Appendix). For each beneficiary group, we also calculated the average number of ES produced or consumed per participant (ES production/consumption richness) as well as the share of beneficiaries in each group that produced and consumed each ES.

3. Results

3.1 Ecosystem service and value type rankings (overall sample means)

The picture-based ES rankings showed clear differences in relative importance between the individual ES (Fig. 3). For example, maize and teff were ranked as the most important ES (median = 2, IQR = 3-1), whereas biodiversity was ranked lowest (median = 9, IQR = 11-8). The distributions of the rankings for each ES were also different from each other (Fig. 3). For example, firewood had a median rank of 6 (IQR =7-5), and most people gave it a relatively moderate ranking, whereas only few people ranked it very high or very low. Sorghum on the other hand had a median rank of 7 (IQR = 11-3), and some people ranked it relatively high or low, but only few people gave it a moderate ranking. Participants (in the sub-sample, n = 164) ascribed most importance to direct use value (mean of 29.85 distributed tokens), followed by relational value (27.33 tokens). Exchange value was much less important to participants (17.75 tokens), with least importance ascribed to intrinsic value (11.46 tokens).

According to the token distribution between the ES for each of the four value types, participants valued the 11 ES for different reasons (Fig. 4). For five out of 11 ES (teff, maize, firewood, sorghum, honey), participants on average ascribed most importance to their direct use value, followed by relational, exchange and intrinsic value. For coffee, on average, most importance was ascribed to its exchange value, followed by relational, direct use and intrinsic value, whereas for khat, relational value was most important, followed by exchange, direct use and intrinsic value. For cattle, eucalyptus and beef, direct use, exchange and relational value were ascribed relatively equal importance (less than 0.5 tokens difference), but with intrinsic value still being least important. Only for biodiversity, participants ascribed most importance to its intrinsic value, followed by direct use, relational and exchange value.

The four value types ascribed to the ES reflected the relative importance of ES to varying degrees. In Fig. 4, ES were ordered by their median rank based on the picture-based ES ranking. Hence, if

a value type reflected the overall ranking well, we should see a gradient from light to dark, i.e. from very important to not important. Whereas direct use and relational value performed relatively well in this assessment, exchange and intrinsic value did not reflect well the picture-based ES ranking. For example, whereas coffee, cattle and khat were on average attributed most exchange value, they only came in third, fourth and sixth place in the overall ranking. Firewood was almost attributed no exchange value, but it was ranked the fifth important ES overall.

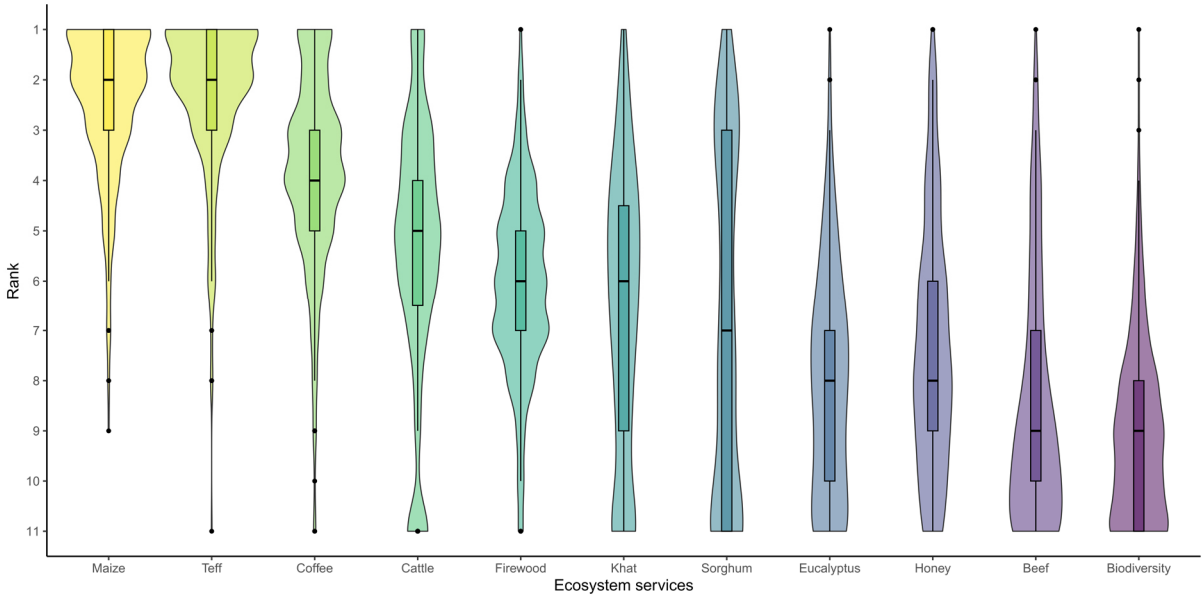

Figure 3. Box and violin plots of ES rankings based on the picture-based ES ranking, where participants were asked to rank pictures of 11 ES based on their general importance (n = 316).

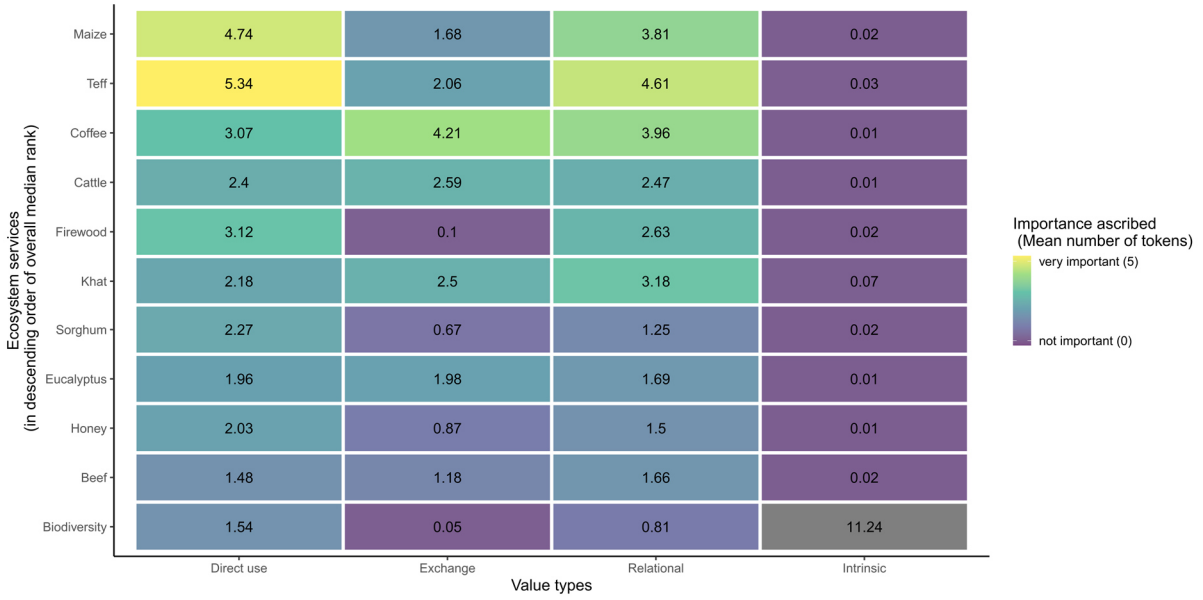

Figure 4. Importance ascribed to each ES within four value types, based on mean number of tokens attributed (n = 164). Participants were asked to indicate a weighted ranking of 11 ES for each value type by distributing 30 tokens within each value type. The lighter the color, the more tokens were attributed to the ES, hence the more important the ES. ES are sorted by their overall median rank based on the picture-based ES ranking. The intrinsic value of biodiversity is indicated in grey due to design considerations, as the inclusion of its very high relative value in the color scale would have rendered other values indistinguishable.

3.2 Ecosystem service and value type rankings for five beneficiary groups

Clustering participants based on their picture-based ES rankings resulted in five beneficiary groups, which we named according to their prioritization of certain ES: the cereal croppers, the cash croppers, the livestock owners, the forest users, and the diverse ES users (Fig. 5, Table 2).

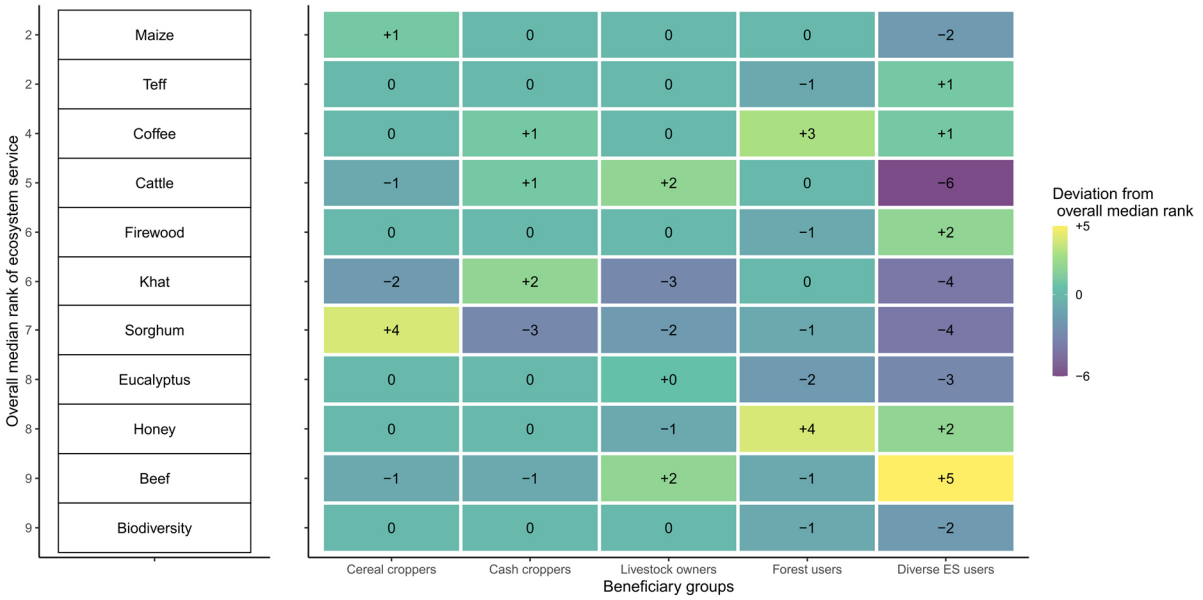

Figure 5. ES sorted by their overall median rank based on the picture-based ES ranking, and deviations from these overall median ranks for each of five beneficiary groups (n = 297). Participants were clustered into five groups based on their picture-based ES ranking. The lighter the color, the more positive the deviation.

Thirty-four percent of the participants formed the *cereal croppers* group and ranked sorghum much higher (+4) and maize higher (+1) than the overall median rank, whereas beef (-1), cattle (-1) and khat (-2) were less important to them. The *cash croppers* group consisted of 34% of the participants who ranked khat (+2) as well as coffee and cattle (+1) higher than the overall median rank, but to whom beef (-1) and sorghum (-3) were less important. Khat and coffee are known as the main cash crops in the study area (Manlosa, Hanspach, et al., 2019). The *livestock owners* group consisted of 12% of the participants who ranked cattle and beef higher than the overall median rank (both +2), whereas honey (-1), sorghum (-2) and khat (-3) were comparatively less important to them. Ten percent of the participants were included in the *forest users* group, and ranked honey (+4) and coffee (+3) much higher than the overall median rank, but teff, firewood, sorghum, beef, biodiversity (all -1) and eucalyptus (-2) were less important to them. The most contrasting group was the *diverse ES users* group with 9% of the participants to whom beef (+5), firewood (+2), honey (+2), teff (+1) and coffee (+1) were comparatively important, but who also ranked maize, biodiversity (both -2), eucalyptus (-3), khat, sorghum (both -4) and cattle (-6) much lower than the overall median rank.

In addition to their differences in ES rankings, the five beneficiary groups differed in their individual characteristics, their social-ecological context (in terms of the kebeles participants lived in, and the ES they produced and consumed), and in how they ascribed value types to ES (Table 2). The beneficiary groups were associated with occupation (being a farmer or not; X-squared = 100.4, df = NA, p-value < 0.01 - with simulated p-value), with a strong positive association between *diverse ES users* and non-farmers (Fig. A2). However, they were not associated with any other individual characteristics (Table 2). There was no significant association between the beneficiary groups and gender (X-squared = 3.0593, df = 4, p-value = 0.55) or wealth (X-squared = 5.9546, df = NA, p-value = 0.19 - with simulated p-value).

Regarding the social-ecological context, the beneficiary groups were associated with the social-ecological groups of kebeles that participants lived in (X-squared = 115.85, df = 12, p-value < 0.01). Besides some weaker associations (0 < Pearson residual < 1), we found strong positive

*Table 2. ES rankings, individual characteristics, social-ecological context, and values ascribed to ES for five beneficiary groups (n = 297). Clustering was based on participants' picture-based ES rankings. VT = value type(s), DU = direct use value, EX = exchange value, REL = relational value, INT = intrinsic value. *Positive association based on chi-square test (1 > Pearson residual > 0). **Strong positive association based on chi-square test (Pearson residual > 1).*

Beneficiary group	**Cereal croppers**	**Cash croppers**	**Livestock owners**	**Forest users**	**Diverse ES users**
Number of beneficiaries	102	101	36	31	27
Picture-based ES ranking					
ES ranked comparatively high	Sorghum, maize	Khat, coffee, cattle	Cattle, beef	Honey, coffee	Beef, firewood, honey, teff, coffee
ES ranked comparatively low	Beef, cattle, khat	Beef, sorghum	Honey, sorghum, khat	Teff, firewood, sorghum, beef, biodiversity, eucalyptus	Maize, biodiversity, eucalyptus, khat, sorghum, cattle
Individual characteristics					
Occupation					
Farmer %	94*	96*	100*	97*	37
Non-farmer %	6	4	0	3	63**
Gender					
Women %	50	41	53	42	52
Men %	50	59	47	58	48
Wealth					
Wealthy %	51	65	67	68	50
Poor %	49	35	33	32	50
Social-ecological context					
Social-ecological kebele group					
Pasture-cropland %	24 *	26 *	36 **	3	15
Khat-cropland %	11	46 **	28 *	16	0
Woody vegetation %	35 **	6	11	65 **	7
Accessible-wealthy %	30 *	23	25	16	78 **
ES production richness	7.29	7.87	7.92	8.45	2.81
ES consumption richness	10.17	10.34	9.89	10.71	8.04
Main producers of	Sorghum	Khat, maize, teff	Beef, cattle, eucalyptus	Biodiversity, coffee, firewood, honey, maize	-
Values based on token distribution (n = 164; deviations by more than one token from overall mean number)					
Relative importance of VTs	+EX +INT	+REL	-	+REL +EX -INT	-REL -EX -INT
Importance ascribed to each ES within VT	+DU sorghum +REL sorghum +INT biodiversity	+EX khat	-	+EX coffee/honey +REL honey -INT biodiversity	+DU beef/coffee/teff -DU cattle/sorghum -EX cattle/coffee/khat +REL coffee -REL cattle/eucalyptus/ firewood/maize/ sorghum/teff -INT biodiversity

associations (Pearson residual > 1) between the *cereal croppers* and the *forest users* and the *woody vegetation* kebele group, the *cash croppers* and the *khat-cropland* group, the *livestock users* and the *pasture-cropland* group, and between the *diverse ES users* and the *accessible-wealthy* group (Table 2, Fig. A3).

Most participants consumed and produced almost all 11 ES (Table A2). The *forest users* had the highest average production and consumption richness (8.45 ES produced and 10.71 ES consumed), whereas the *diverse ES users* had the lowest respective values (2.81 and 8.04; Table 2). The relative importance of ES in each beneficiary group was more reflected by ES production rather than their consumption, except for the *diverse ES users* (Table 2, Table A2). For example, the share of *livestock owners* that produced beef or cattle (so those ES that were ranked higher than the overall median) was highest compared with the other groups (e.g. for beef: 42% of the *livestock owners* produced beef, compared to 25, 23, 26, and 19% in the other groups). Participants in the *livestock owners* group were thus the "main producers of" beef (Table 2). The same held true for sorghum for the *cereal croppers*, for khat for the *cash croppers* as well as for coffee and honey for the *forest users*. In contrast, in the *diverse ES users* group, each ES was produced by fewer participants compared to the other groups (Table A2). A similar share of participants in this group compared to the others consumed beef, coffee, firewood, honey, maize and teff (which were ranked highest in this group), whereas the share of participants that consumed the remaining ES was comparatively low (Table A2).

Whereas the overall order of relative importance of the four value types remained the same in each group (direct use value > relational value > exchange value > intrinsic value), they still differed in the exact importance they ascribed to each value type (Fig. 6B, Table 2; considering deviations by more than one token from overall mean number of distributed tokens in Fig. 6A). The beneficiary groups showed no differences for direct use value. Relational value was comparatively more important to *cash croppers* and *forest users*, and less important to *diverse ES users*. Exchange value was comparatively more important to *cereal croppers* and *forest users*, and again less important to the *diverse ES users*. Intrinsic value was comparatively important to *cereal croppers*, less important to *forest users*, and again least important to *diverse ES users*.

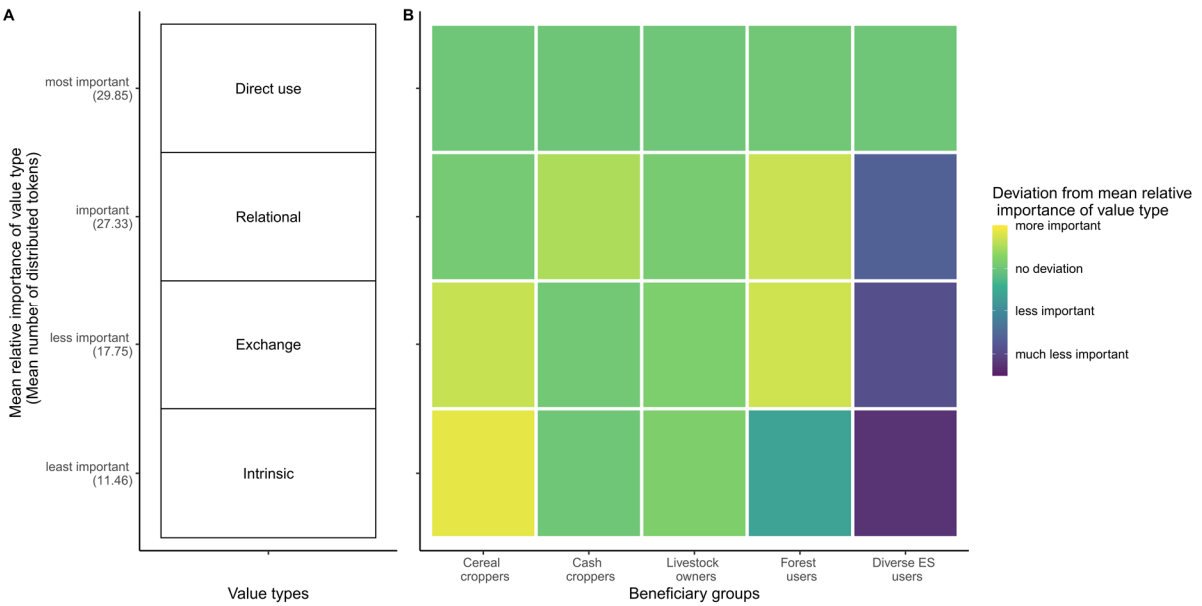

Figure 6. Relative importance ascribed to each of four value types (A; based on mean number of distributed tokens, n = 164), and deviations from these means in each of five beneficiary groups (B). Participants were asked to indicate a weighted ranking of 11 ES for each value type by distributing 30 tokens within each value type, with the option of not distributing tokens if the value type was relatively unimportant to them. Participants were clustered into five beneficiary groups based on their picture-based ES ranking (see section 3.2). The lighter the color, the more important the value type in the beneficiary group compared to the average.

Participants in each of the five beneficiary groups ascribed different types of values to their prioritized ES (Table 2, Figs A4-A8; considering deviations by more than one token from the overall mean number of tokens shown in Fig. 4). For example, the *cereal croppers* ranked sorghum comparatively high, and they ascribed more importance to its direct use and its relational value than participants in the other groups. The *cash croppers* ranked khat relatively high, and ascribed more importance to its exchange value. The *forest users* ranked honey and coffee comparatively high, and the exchange value of coffee and honey and the relational value of honey were more important to them than to participants in the other groups. The *diverse ES users* ranked inter alia beef, teff and coffee comparatively high, and they ascribed more importance to the direct use value of these ES, and to the relational value of coffee.

4. Discussion

We investigated the relative importance and the plural values that beneficiaries in rural southwestern Ethiopia ascribed to ES, their relationship, and the influence of individual and social-ecological contexts on the relative importance of ES. We discuss the specific empirical and the general methodological insights as well as implications for decision-making in more detail below.

4.1 Empirical insights

4.1.1 Overall sample

We assessed the relative importance that people ascribed to 11 different ES and to four different value types. Overall, maize and teff were ranked the most important ES (median = 2), whereas biodiversity was ranked lowest (median = 9, Fig. 3). Other studies have also shown that ES that are directly related to people's livelihoods were ascribed most importance (Hartel et al., 2014; Lau et al., 2019; Tauro et al., 2018). In contrast to our results, some studies found that biodiversity-related ES, such as habitat protection or satisfaction for conserving biodiversity, were considered more important than other services (Lau et al., 2018; Martín-López et al., 2012).

On average, direct use and relational value were the most important value types, whereas exchange and intrinsic value were judged less important (Fig. 6A). Recently, in the study area, direct ES flows have declined and access to emerging market-oriented services with indirect benefits has increased (Schultner et al., 2021). However, the study area is still a largely subsistence-based landscape and direct use value thus plays an important role (Manlosa, Hanspach, et al., 2019; Schultner et al., 2021). The importance of relational value in the study area is also not negligible, and a range of local traditions and experiences connected to ES production and consumption make relational value more important to local people than exchange and intrinsic value. Our findings suggest that many of the ES studied here support the generation and maintenance of social cohesion (Chan et al., 2016). Beneficiaries highlighted multiple ways in which ES brought them together with other people. For example, the production of honey (beehive making and hanging), khat chewing, and coffee drinking and ceremonies increased social interactions and relationships (based on field notes during data collection).

Hence, more generally, beneficiaries ascribed diverse and often multiple values to a given ES (Fig. 4), and ostensibly material services can have crucial non-material dimensions, such as the social cohesion aspects of khat chewing and coffee ceremonies in the study area (Chan et al., 2012; Hirons, Comberti, & Dunford, 2016). Such plural values seem to be common, as for example people in European farming landscapes understood local food production both as a provisioning and as a cultural ES (Plieninger, Torralba, Hartel, & Fagerholm, 2019), and while gleaning played a role for subsistence to women in Timor-Leste, socializing or spending time in nature were even more important (Grantham, Lau, & Kleiber, 2020). The nature's contributions to people (NCP) framework acknowledges that material and non-material contributions can often be interlinked, with culture permeating through all groups of contributions, and that context-specific perspectives can include

multiple ways of understanding and categorizing relationships between people and nature (Díaz et al., 2015; Díaz et al., 2018). Our results raise questions regarding the utility of categorizing the benefits of nature to humans solely in terms of the types of services or contributions they provide (Díaz et al., 2018; Millennium Ecosystem Assessment, 2005). Rather, the focus should be on the types of values ascribed to specific ecosystem structures or functions (Kenter, 2018).

Regarding the relationship between the relative importance of ES and ascribed values, we found that the relative ranking of ES within the different value types matched the general ES ranking to varying degrees. Whereas direct use and relational value reflected the general importance of ES relatively well, exchange and intrinsic value did not perform well in this assessment. This is in line with other research, which found, for example, that monetary values of wetlands in Asia correlated negatively with the nonmonetary values held by some of the most dependent groups, which were assessed by an importance score (Brooks et al., 2014), or that ES with low market or exchange values were still highly appreciated in some villages in Southwestern Ethiopia (Tadesse et al., 2014).

4.1.2 Beneficiary groups

Beneficiaries differed in the relative importance they ascribed to each ES through the picture-based ranking, and each of the five groups ranked a different set of ES higher than the other groups. Different individual and social-ecological contexts influenced the assignment of importance to ES. For the individual characteristics of beneficiaries, there was no association between the beneficiary groups and gender or wealth (Table 2). This is only partly in line with the literature, since we would have expected some differences in the relative importance of ES by gender and wealth that were found by other studies (Coelho-Junior et al., 2021; Lau et al., 2018). However, similar to our results (non-farmers were associated with the *diverse ES users* group, and 94% of all non-farmers in our sample lived in the town), both occupation and the urban-rural gradient can explain differences in the relative importance of ES (Brooks et al., 2014; Lapointe et al., 2020; Martín-López et al., 2012).

Moreover, the relative importance of ES was clearly connected to the social-ecological context of beneficiaries, both to the types of kebeles they lived in and in terms of patterns of ES production and consumption (Table 2, Fig. A3, Table A2). For each of the five beneficiary groups, we found a strong positive association with one of the four kebele groups. For example, the *livestock owners* group was strongly positively associated with the *pasture-cropland* kebele group, which was characterized inter alia by high availability of pasture (for a more detailed discussion see Appendix). The five beneficiary groups showed varying degrees of production and consumption for each ES, where beneficiaries generally prioritized those ES that were produced by their group more than by other groups, except for the *diverse ES users* (where beneficiaries prioritized ES they consumed, and only produced few ES). The influence of the social-ecological context on assigned relative importance of ES has also been recognized elsewhere. For example, perceptions of the importance of mangrove ES differed between communities, likely due to differences in access to ES and in main economic activities (Reyes-Arroyo et al., 2021). The relative importance of ES as assessed by cattle ranchers in Mexico was associated with their livelihood, in terms of diversity of productive activities and also generational changes in livelihoods (Tauro et al., 2018).

The relative importance of value types overall was consistent between the five beneficiary groups (direct use value > relational value > exchange value > intrinsic value; Fig. 6B). However, relational value was comparatively more important to *cash croppers* and *forest users*. Exchange value, on the other hand, was perceived as relatively more important by *cereal croppers* and *forest users*. The likelihood to express certain value types may depend on people's motivations (e.g. egoistic vs. altruistic), their place of residence, their level of education, age, or their cultural identity (Arias-Arévalo et al., 2017; Elbakidze et al., 2021; Lau et al., 2019). In our study, diverse activities were connected to the production and consumption of ES that beneficiaries associated with relational value (see above). In contrast, the importance of exchange value is likely to depend on the contribution of market activities to people's livelihoods. Relational, exchange and intrinsic value were all judged comparatively less important by the *diverse ES users*, which consisted mostly of non-farmers living in town. Non-

farmers might ascribe less relational and exchange value to ES, because they are less in contact with nature and also rely less on it for income generation. Support for a disconnection between urban residents and nature, with a consequential loss of relational and intrinsic values, has for example been reported in a study by Arias-Arévalo et al. (2017), and is a general concern in many societies (Riechers, Martín-López, & Fischer, 2021). However, understanding the exact reasons behind the importance ascribed to the different value types in the beneficiary groups requires further research.

Each of the five beneficiary groups ascribed different types of values to their prioritized ES (Figs A4-A8). For example, sorghum was prioritized for its direct use and relational value, but honey for its exchange and relational value. These value ascriptions were not necessarily consistent with the relative importance of value types in the groups (e.g. *cash croppers* prioritized relational value in general, but prioritized khat in particular for its exchange value). These findings mirror other studies, for example, Arias-Arévalo et al. (2017) found that people emphasize diverse values, especially relational values, in their narratives of why ES are important to them. In coastal communities in Papua New Guinea, people ascribed most importance to provisioning ES, but mentioned different aspects of well-being when explaining why they mattered to them, often referring to bequest values (Lau et al., 2019). When analyzing wetland ES in Greece, Maniatakou et al. (2020) found five perspectives of the relative importance of ES, and each reflected divergent understandings of relational and instrumental values.

4.2 Methodological insights

Even though the need for plural valuation of nature is increasingly recognized (for example in initiatives such as IPBES, Hill et al., 2021), ES valuation is still often based on a single commensurable metric (often in monetary terms, Arias-Arévalo et al., 2018), which in turn implies a single type of value ascription. In this study, we allowed the association of multiple value types with a given ES (in our case, up to four value types could be ascribed to each of 11 ES), and this proved useful in assessing and comparing the plural values ascribed to ES. To elicit such diverse values ascribed to ES, we developed our own method using tokens, inspired by approaches in the literature (placing counters on ES to evaluate importance – see Hicks et al., 2015; Lau et al., 2018, 2019). From our experience, tokens as a vehicle to assess values were useful, because they were tangible. They also allowed for a flexible and differentiated picture of how beneficiaries ascribed different types of value to ES in the form of a consistent weighted ranking.

While it is relatively simple to define direct use and exchange value, relational and intrinsic value are more complex and multi-dimensional notions, and how they are defined and operationalized is likely to influence value ascription. For relational values, we chose to focus on social cohesion, using the formulation "because it brings people together". We found that beneficiaries responded well to this formulation, which we had tested in a pilot study, and attributed a lot of importance to this value type (Fig. 6A). However, there are multiple other dimensions within relational values that could have been explored (see Chan et al. (2016) and Riechers, Balázsi, et al. (2021) for a detailed discussion). Communicating intrinsic values appeared to be the most challenging. As could be expected, biodiversity was ascribed most intrinsic value compared to the other ES (Fig. 4). However, certain observations made us less confident of our results related to both intrinsic value and biodiversity. The formulation we used to ask about intrinsic value ("because it simply exists without any benefit to you") might have prompted beneficiaries to think about intrinsic value rather as a "disvalue" (Lliso, Lenzi, Muraca, Chan, & Pascual, 2022), and, respectively, about biodiversity as a "disservice" (Shackleton et al., 2016). Wild animals were often mentioned by beneficiaries when talking about biodiversity, which are a disservice to smallholders due to crop raiding (Ango, Börjeson, Senbeta, Hylander, & Fischer, 2014; Dorresteijn et al., 2017). For example, one participant mentioned that "animal biodiversity is not important, simply exists without any benefit, even harms production" (field notes). Through our formulation for intrinsic value ("because it simply exists without any benefit to you"), we might have pre-assigned lesser worth to this value type and/or the ES it is ascribed to, and biodiversity might have stood out in a peculiar way among a range of (what is typically categorized as) provisioning services. Therefore, whereas pluralistic valuation

approaches are important, there is a distinct possibility of vehicle or information bias (where the value framings influence the ascribed values) in the elicitation of such values. However, we would note that such issues are also present in more standard valuation approaches (e.g. vehicle bias in contingent valuation studies; Boyle, 2003; Venkatachalam, 2004). Moreover, we asked beneficiaries to give a weighted ranking of ES within different value types. In contrast, we could also have asked for a ranking of value types for each ES, with potentially differing results. Future research could investigate whether such differing approaches to the same method – token distribution among ES and value types – generate different results (e.g. are direct use and relational values still considered more important than exchange value if assessed for each ES separately?).

Whereas disaggregated valuation is important, communicating the results of such multidimensional value elicitations is challenging (Brück et al., 2022; Daw, Brown, Rosendo, & Pomeroy, 2011). In this study, we provide an approach to partly re-aggregate the ES ranking data, in order to reduce dimensionality, while keeping important distinctions. Here, the use of statistical clustering of beneficiaries based on the ES ranking helped to organize and aggregate the data. This approach allowed a meaningful interpretation of the data and insights into the relationship between the relative importance of ES and beneficiaries' individual characteristics and social-ecological context. Other characteristics than the ES ranking results could have been used for clustering beneficiaries, and this would have likely resulted in differing patterns and interpretations of the disaggregated data. This tension between disaggregated analysis and aggregated presentation of results is an area requiring further research. Whereas the value types ascribed to specific ES partly explained why beneficiaries in certain groups ranked some ES higher, we were not able to find such reasons for each prioritized ES (for example, the preferences for cattle and beef of the *livestock owners* were not reflected in the values ascribed to those ES). Follow-up investigations may thus be needed to understand the exact influence of values on importance for specific groups.

4.3 Insights for decision-making

In this section, we do not suggest concrete policies, but based on our empirical and methodological insights, discuss the relevance of our results for decision-making. First, landscape management in our study area should consider other types of values ascribed to ES beyond exchange value. The focus of current development plans is on specialization and market integration, which are strongly encouraged by the government, and expected or even favored by many stakeholders in the study area (Federal Democratic Republic of Ethiopia, National Planning Commission, 2016; Jiren, Dorresteijn, et al., 2020; Jiren, Hanspach, et al., 2020). Over the past decades, ES production in our study area has shifted from subsistence to marketed crops, and access to cash crops with indirect benefits increased (Schultner et al., 2021), reflecting a focus on commercialization and the exchange value of ES. However, we clearly show here that not only exchange value, but a range of different values can be ascribed to ES that are currently produced and consumed in the landscape. This seems even more urgent when considering that exchange value in our case was much less important to people than direct use and relational value, and that exchange value ascribed to ES did not reflect well the overall importance ascribed to ES for people's livelihoods. A shift towards more intensified and commercialized agriculture, without careful considerations of potential implications for people's livelihoods and connected values, might lead to unforeseen losses of certain value types other than exchange value, and particularly of relational values. Such developments have already been described elsewhere, for example where relational values were negatively affected by adoption of large-scale irrigation or through landscape simplification (Albizua, Pascual, & Corbera, 2019; Riechers, Martín-López, & Fischer, 2021). In our study area, the relational value and the exchange value of coffee were ascribed similar importance, even though coffee is considered a key cash crop. Regarding the future of coffee in the study area, the decision whether to prioritize export coffee production, or to establish a biosphere reserve that combines sustainable agriculture, eco-coffee production, and tourism opportunities, should consider the diverse values people ascribe to coffee, seeing that such a decision is likely to largely influence people's livelihoods and connected values (Jiren, Hanspach, et al., 2020).

Second, we encourage landscape management to be aware of people's diverse ES rankings and values that are at least partly grounded in their social-ecological context, to be able to adequately and sustainably plan future developments. We found that beneficiaries could be grouped into five clusters based on their ES rankings, and that these groups differed in their social-ecological context. Previous research had already shown that future development under different scenarios differed substantially between the four social-ecological kebele groups (Duguma et al., 2022). Smallholders in our study area, and in heterogeneous landscapes elsewhere, should thus not be treated as a homogeneous group, but rather differentiated based on their social-ecological context.

5. Conclusion

Whereas presenting and interpreting results based on disaggregated data was challenging due to its multi-dimensionality, our plural approach proved useful in better understanding the relative importance of ES, values ascribed to ES and the relationship between them. For our Ethiopian case study, we found that maize and teff were ranked as most important, and direct use and relational value were the most important value types. Beneficiaries often ascribed multiple values to each ES, and exchange value alone did not reflect well the general importance that beneficiaries ascribed to ES. We derived five beneficiary groups that each prioritized different sets of ES. The social-ecological context of the kebele groups that were positively associated with each of the five beneficiary groups reflected relatively well the respective relative importance of certain ES. Whereas the relative importance of value types overall was consistent between the five groups of beneficiaries (direct use value > relational value > exchange value > intrinsic value), beneficiaries in each of the five groups ascribed different types of values to their prioritized ES. These varied from group to group, and were not necessarily consistent with the value types that were generally ranked highest by the beneficiary groups. Our study undertook an approach to assessing reasons behind ES rankings, and highlights the continued need for plural valuation of ES, in order to match the complex benefits of ES in social-ecological systems. Based on our results, we recommend that sustainable landscape management in Ethiopia should take into account people's diverse ES rankings and values as well as other types of values ascribed to ES apart from exchange value.

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Author contributions

Maria Brück and David J. Abson conceived the ideas and designed methodology; Birhanu Bekele Negash and Dadi Feyisa Damu collected the data; Maria Brück and David J. Abson analyzed the data. All authors interpreted the data and contributed critically to the drafts and gave final approval for publication. Our study brings together authors from a number of different countries, including scientists based in the country where the study was carried out.

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Appendix

Methods

Kebeles and their social-ecological groups

Table A1. The eight kebeles (smallest administrative units in Ethiopia) and one town that were sampled in our study, plus their woredas (districts) and social-ecological kebele groups.

Kebele	Woreda	Social-ecological kebele group
Chanido	Gumay	pasture-cropland
Difo Mani	Setema	woody vegetation
Done	Setema	pasture-cropland
Duseta	Gera	khat-cropland
Gurariso	Gera	woody vegetation
Gure Dako	Gera	khat-cropland
Kuda Kefo	Gumay	accessible-wealthy
Setema Kecha	Setema	accessible-wealthy
Toba Town	Gumay	accessible-wealthy

The "pasture-cropland group" was characterized by high availability of pasture and arable land. It also had the lowest cover of woody vegetation and low levels of coffee forest, khat, and eucalyptus. The "khat-cropland group" had a distinctly high availability of khat and arable land and was located at higher altitudes, with low coffee forest availability and the lowest wealth index. The "woody vegetation group" had a high extent of woody vegetation cover, high coffee forest availability, high importance of honey production, and was relatively remote. The "accessible-wealthy group" had large extents of eucalyptus plantations, and was relatively accessible and wealthy (Duguma et al., 2022).

Questionnaire

Introduction

Read the following text to potential participants.

"We are a team of researchers of Addis Ababa University and Leuphana University Lüneburg in Germany. With our research, we want to understand better why nature is important to you and other people in the area. We will go to eight different kebeles and also to Jimma town to ask many different people.

I would like to ask you to be part of this survey. By participating in this survey, you can contribute to a better understanding of your landscape, which can also help policy makers to make better decisions. The survey will take about 30 minutes. We will ask you questions about natural products and benefits, and do some exercises with you to understand how important they are to you and why.

We are university-based and not working for any other organizations. Your name will not be used in any publications. Your participation is voluntary, you are free to skip any questions if you do not want to answer them. You can also stop your participation at any time if you feel uncomfortable. We will store all information we obtain safely, so that only our research team can access them.

Do you have any questions?

Do you agree to participate? Do you agree that we can use, analyze and store the information you provide?"

Document if participant agrees on data sheet 1. Fill out the general information at the top of data sheet 1 (number of interview, interviewer, date, place). (For number of interview you should start with number 1 and then put consecutive numbers for each interview you do.) If there is anything interesting that comes up throughout the interview, please use the "notes" section on data sheet 1.

Sociodemographic data

"What is your occupation? How many cattle and how much land do you own?"

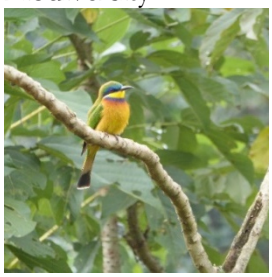
Fill out on data sheet 1. Cattle = number of cattle owned (includes, oxen, cows, and bull; excludes shared); Land size = total land size in hectare (certified land, independent of its use - includes land used for crops, grazing, coffee, and home gardens; excludes shared); Plus for people in kebeles: observe gender and wealth status (by checking their house – tin or grass roof).

Natural products and benefits

Show the pictures to the participant.

Beef

Biodiversity



Cattle

Coffee

Eucalyptus

Firewood

Honey

Khat

Maize

Sorghum

Teff

"Let's talk about different natural products and benefits and their role in your household's life. Here you can see some pictures: beef, biodiversity, cattle, coffee, eucalyptus, firewood, honey, khat, maize, sorghum, teff. Do you understand all of them?"

Make sure participant recognizes and understands all pictures. For further explanation (if needed):

- *Biodiversity means the variety of life. For example, it means that there are many different species of trees or birds in your landscape.*
- *For eucalyptus, please think of small and medium-sized eucalyptus that you use for tools or building materials.*

"Remember that you don't need to talk about all the products and benefits if you don't feel comfortable. (*For example, if people prefer not to talk about khat, you can check the fourth column "prefer not to answer".*)

Which of them does your household produce?

Which of them does your household consume or enjoy?"

Check boxes on data sheet 1.

"Which of them are not important for your household at all?"

Check boxes on data sheet 1 and remove pictures that are not considered important (or participant prefers not to talk about).

General ranking of natural products and benefits

Move now to data sheet 2A. Fill out general information at the top of data sheet 2A (number of interview, interviewer, date, place). Make sure to put the same number of interview as on data sheet 1.

"How important is each natural product or benefit to you in general? Please move the pictures up and down, with the most important one at the top."

Arrange pictures in the first column on data sheet 2A. Try to get people to really give an order to the pictures (none should be ranked equally).

"Can you think of any other natural products or benefits that are important to you?"

Note on data sheet 1.

Exercise A (sort by column, data sheet 2A)

Use 30 coffee beans for each column (so you need 120 in total). Put 30 beans in each column at the top of data sheet 2A.

"There are different reasons why natural products or benefits can be important in your life. We would like to talk about a number of different reasons now one after the other.

The four different reasons are:

(1) because you directly use or consume it
(2) because you can sell or trade it
(3) because it brings people together (for example, while harvesting or preparing and consuming)
(4) because it simply exists without any benefit to you

In this first column, we would like to know how important each natural product or benefit is to you because you directly use or consume it? Here you have 30 coffee beans. You can distribute them between all natural products and benefits. You can put more than one bean in each box. You

can leave some boxes empty. You can also leave all beans at the top if nothing is important to you because you directly use or consume it. (*Let participant distribute the coffee beans.)*

In the second column, we would like to know how important each natural product or benefit is to you because you can sell or trade it? Again you can distribute 30 coffee beans. (*Let participant distribute the coffee beans.)*

In the third column, we would like to know how important each natural product or benefit is for bringing people together (for example, while harvesting or preparing and consuming)? Again you can distribute 30 coffee beans. (*Let participant distribute the coffee beans.)*

In the last column, we would like to know how important each natural product or benefit is to you because it simply exists without any benefit to you? Again you can distribute 30 coffee beans. (*Let participant distribute the coffee beans.)*

Are you happy with how you distributed the coffee beans? Would you like to make any adjustments?

Can you think of any other reasons why natural products or benefits are important to you?"

Note additional reasons on data sheet 1.

"Thank you very much for sharing your time and this valuable information with us. Do you have any questions? Thank you and have a good day!"

On data sheet 2A, write the number of beans in each box next to the beans. Take pictures of both data sheets. You can then erase all information to continue with the next person.

R packages

For general data wrangling, we used the following R packages:

- Corrplot (Wei and Simko, 2021)
- Dplyr (Wickham et al., 2022)
- Ggpubr (Kassambara, 2020)
- Naniar (Tierney et al., 2021)
- Readxl (Wickham and Bryan, 2019)
- Rstatix (Kassambara, 2021)
- Tidyverse (Wickham and et al., 2019)
- Writexl (Ooms, 2021)

For the hierarchical clustering, we used:

- Amap (Lucas, 2019)
- NbClust (Charrad et al., 2014)
- Cluster (Maechler et al., 2021)

Data processing

To ensure consistency of the data, we made some adjustments to the number of tokens. We cross-checked each record by comparing numbers recorded in the data sheets against pictures of the original data sheets with tokens. If the sum of tokens in a column was unequal to 30, we normalized the token counts in the respective column to 30 (dividing by the actual sum and multiplying by 30).

Type of roof did not prove to be a useful, distinct measure of wealth, because most of the participants had tin roofs. Number of cattle and land size were significantly positively correlated (Kendall's tau = 0.4 at the 1% level), and number of cattle had fewer missing values, so we decided to use number of cattle as our wealth indicator. For an additional check, we also created a wealth dummy variable based on land size, split at its median of 1 ha. All participants with a land size of 1 ha or larger were categorized as wealthy. Same as in our results with the wealth variable based on number of cattle, there was no significant association between the clusters and wealth (X-squared = 5.6077, df = NA, p-value = 0.22 - with simulated p-value).

Hierarchical clustering

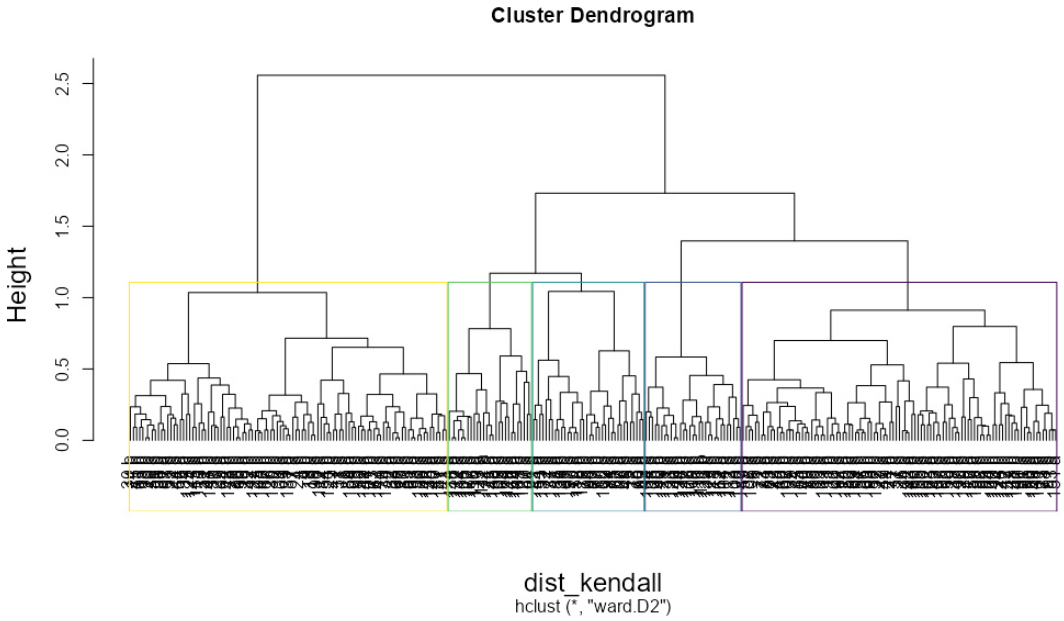


Figure A1. Dendrogram of hierarchical clustering analysis based on picture-based rankings of 11 ES (n = 297). The five clusters were derived considering group interpretability and a range of statistical tests.

We used "NbClust" (Package NbClust, Charrad et al., 2014) to calculate multiple indices for determining the number of clusters, inter alia the Calinski-Harabasz criterion and the Dunn index. Seven indices suggested two as the best number of clusters, five indices suggested three clusters, but five or six clusters were suggested each by four indices as the best number. We compared all these potential solutions based on their resulting group interpretability, and we decided for five clusters, because this delivered easily interpretable results. We additionally calculated the agglomerative coefficient ("agnes" in Cluster package, Maechler et al., 2021), which describes the strength of the clustering structure (Kaufman and Rousseeuw, 1990). Our calculated value was 0.96, and a value close to 1 means that a very clear clustering structure has been identified.

Results

Relative importance of ecosystem services, individual characteristics and the social-ecological context

Individual characteristics: Occupation

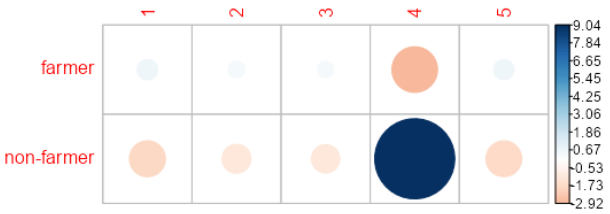


Figure A2. Pearson residuals of each cell of the contingency table of clusters (columns) and occupation (rows), visualized in a correlogram. The size of the circle indicates the magnitude of the residual. Positive residuals are in blue and specify an attraction (positive association) between the corresponding row and column variables. Negative residuals are in red, implying a repulsion (negative association) between the corresponding row and column variables. Clusters were 1 = livestock owners, 2 = cereal croppers, 3 = forest users, 4 = diverse ES users, 5 = cash croppers.

Social-ecological kebele groups

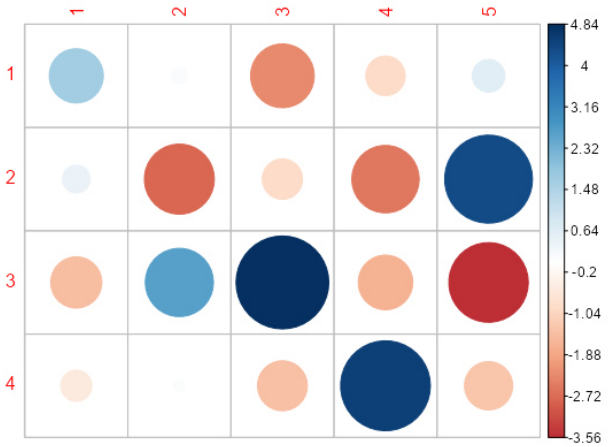


Figure A3. Pearson residuals of each cell of the contingency table of clusters (columns) and social-ecological kebele groups (rows), visualized in a correlogram. Clusters were 1 = livestock owners, 2 = cereal croppers, 3 = forest users, 4 = diverse ES users, 5 = cash croppers. Social-ecological kebele groups were 1 = pasture-cropland, 2 = khat-cropland, 3 = woody vegetation, 4 = accessible-wealthy.

Ecosystem services produced and consumed

Table A2. Ecosystem services produced and consumed in each beneficiary group, plus ecosystem service richness. For each beneficiary group, we calculated the share of participants that produced/consumed each ES. Richness indicates the number of ES produced or consumed on average per participant in each group.

Ecosystem service	**Type**	**Beneficiary group**				
		Cereal crop-pers	Cash croppers	Livestock owners	Forest users	Diverse ES users
Beef	produced	0.25	0.19	0.42	0.23	0.26
Beef	consumed	0.89	0.93	0.81	0.94	0.96
Biodiversity	produced	0.83	0.88	0.92	0.94	0.30
Biodiversity	consumed	0.83	0.94	0.89	0.97	0.30
Cattle	produced	0.76	0.93	0.94	0.90	0.19
Cattle	consumed	0.87	0.98	0.94	0.97	0.48
Coffee	produced	0.76	0.88	0.83	1.00	0.37
Coffee	consumed	0.99	1.00	1.00	1.00	1.00
Eucalyptus	produced	0.61	0.78	0.83	0.74	0.19
Eucalyptus	consumed	0.90	0.96	0.97	0.97	0.44
Firewood	produced	0.83	0.90	0.78	0.97	0.33
Firewood	consumed	0.99	0.99	1.00	1.00	0.93
Honey	produced	0.39	0.41	0.47	0.87	0.19
Honey	consumed	0.91	0.94	0.92	1.00	1.00
Khat	produced	0.54	0.92	0.58	0.87	0.23
Khat	consumed	0.78	0.98	0.72	0.97	0.58
Maize	produced	0.91	0.97	0.94	0.97	0.33
Maize	consumed	1.00	0.99	1.00	1.00	1.00
Sorghum	produced	0.55	0.08	0.28	0.13	0.11
Sorghum	consumed	1.00	0.64	0.64	0.93	0.37
Teff	produced	0.86	0.93	0.92	0.90	0.33
Teff	consumed	1.00	0.98	1.00	1.00	1.00
Richness	produced	7.29	7.87	7.92	8.45	2.81
Richness	consumed	10.17	10.34	9.89	10.71	8.04

Values ascribed to each ecosystem service in the five beneficiary groups

Figure A4. Deviations from overall mean importance for each ES within each of four value types (indicated by deviations in number of tokens), for the cereal croppers. Participants were asked to indicate a weighted ranking of 11 ES for each value type by distributing 30 tokens. The lighter the color, the more tokens were attributed to the ES compared to the overall mean, hence the more important the ES within the value type for the beneficiary group. ES sorted by their overall median rank based on the picture-based ES ranking.

Figure A5. Deviations from overall mean importance for each ES within each of four value types, for the cash croppers.

Figure A6. Deviations from overall mean importance for each ES within each of four value types, for the livestock owners.

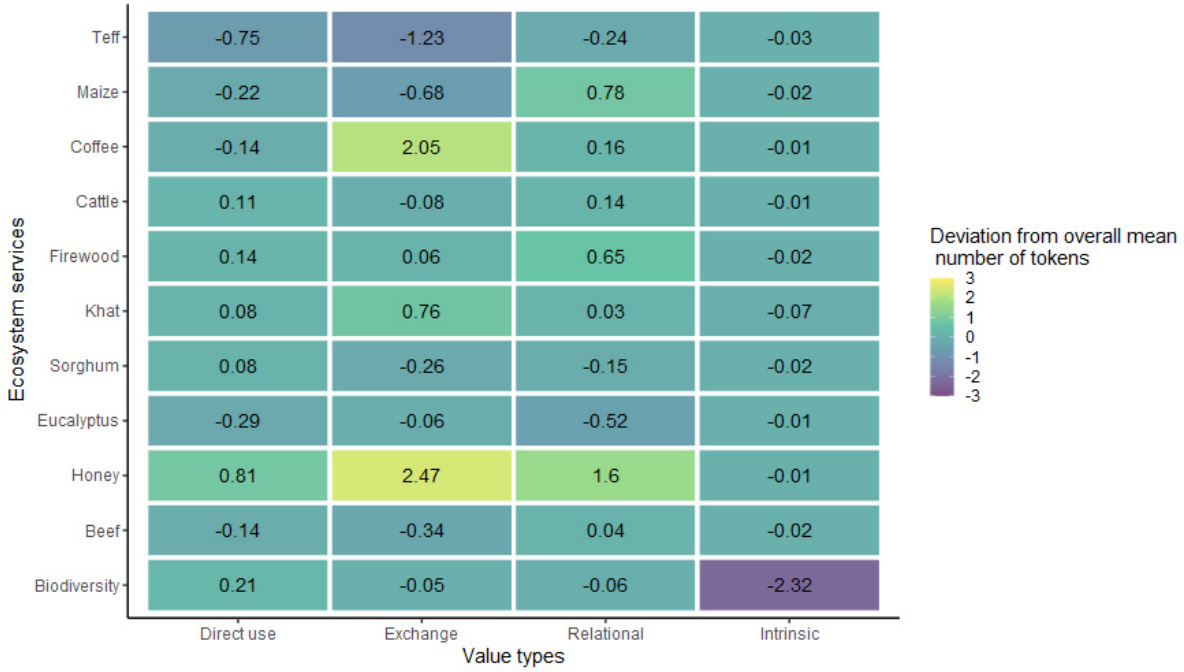


Figure A7. Deviations from overall mean importance for each ES within each of four value types, for the forest users.

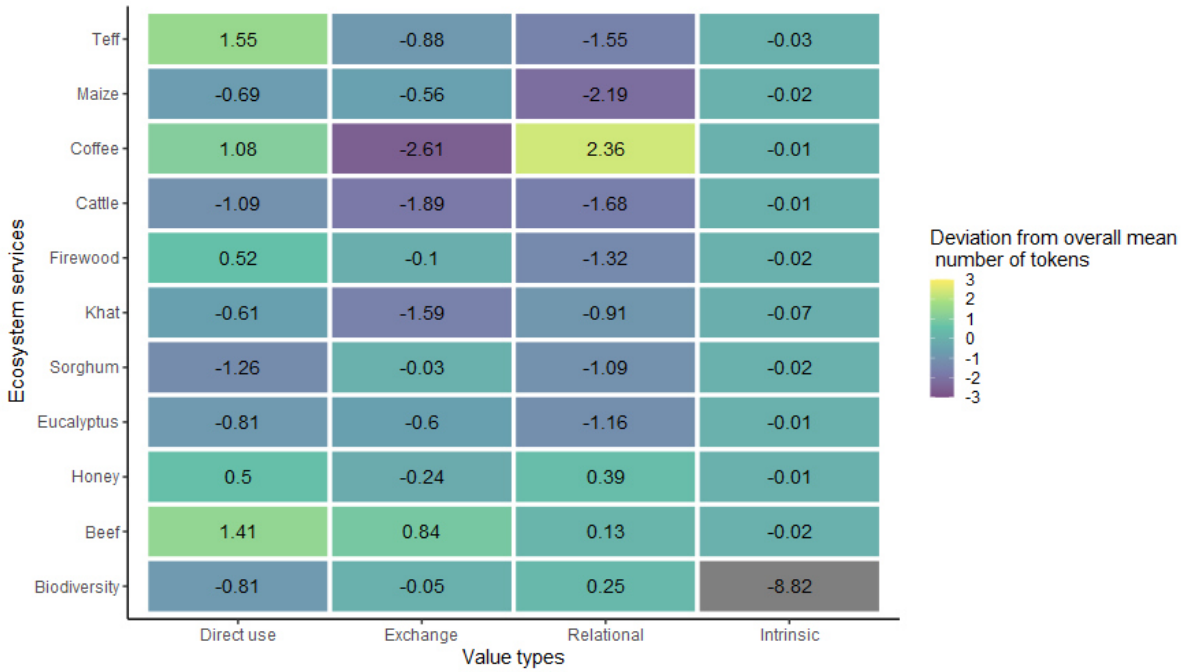


Figure A8. Deviations from overall mean importance for each ES within each of four value types, for the diverse ES users.

Discussion

Ecosystem service rankings and the social-ecological context

For each of the five beneficiary groups, we found a strong positive association with one of the four kebele groups (and sometimes additional associations with other kebele groups). All in all, the social-ecological contexts of the kebele groups that were positively associated with each beneficiary group reflected relatively well the respective relative importance of ES.

The *cereal croppers* were strongly positively associated with the *woody vegetation* kebele group, and also positively associated with the *pasture-cropland* and the *accessible-wealthy* kebele group. It seems that beneficiaries in this group came from diverse social-ecological contexts, but what unified them is their strong preference for sorghum that goes along with its production. According to some field notes, the production of sorghum was limited in certain areas due to its slow growth rate and low productivity, disease susceptibility, and climatic and soil conditions.

The *cash croppers* were strongly positively associated with the *khat-cropland* kebele group, and also positively associated with the *pasture-cropland* kebele group, which together made up more than two thirds of the beneficiaries in this group. The *pasture-cropland* group was characterized by high availability of pasture and arable land, whereas the *khat-cropland* group had high availability of khat and arable land and was located at higher altitudes (Duguma et al., 2022).

The *livestock owners* were strongly positively associated with the *pasture-cropland* kebele group, but also positively associated with the *khat-cropland* kebele group, which together provided more than two thirds of the beneficiaries in this group. The social-ecological context based on the kebele groups was thus similar to the *cash croppers*, but more connected to the *pasture-cropland* kebele group with its high availability of pasture and arable land. Beef and cattle need pasture for grazing, and beef were often more prominent in our study area in kebeles with higher altitudes (Brück et al., 2023), so the associated kebele groups reflect the preference for beef and cattle relatively well.

The *forest users*, who prioritized coffee and honey, were strongly associated with the *woody vegetation* kebele group, and 65% of beneficiaries in the group belonged to this kebele group. Fittingly, the woody vegetation kebele group was characterized by a high extent of woody vegetation cover as well as high coffee forest availability and high importance of honey production (Duguma et al., 2022).

75% of the *diverse ES users* belonged to the *accessible-wealthy* kebele group (we also found a strong positive association), which consists of kebeles that were relatively accessible and wealthy (Duguma et al., 2022). The distinction between urban and rural life plays a role here, seeing that 94% of all non-farmers in our sample lived in the town, and we found that non-farmers were positively associated with the *diverse ES users* group. Towns are more accessible and wealthier in our study area, so participants' preferences for ES which are needed for urban life (beef, firewood, honey, teff, coffee), and the fact that they give less priority to other ES that are more connected to a production-oriented lifestyle, reflected their mostly urban livelihood relatively well.

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Chapter V: A social-ecological approach to support equitable land use decision making

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Under Review in Ambio

A social-ecological approach to support equitable land use decision-making

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Abstract

Human-driven land use change can result in unequitable outcomes in the provision and appropriation of ecosystem services (ES). To better address equity-related effects of land use change in decision-making, analyses of land use and ES changes under different land use management alternatives should incorporate ecological and social information, and take a disaggregated approach to ES analysis. Because such approaches are still scarce in the literature, we present a generalized social-ecological approach to support equitable land use decision-making, and an example of its application to a case study in southwestern Ethiopia. We propose a six-step approach that combines scenario planning with equity-focused, disaggregated analyses of ES. Its application in our study area made equity-related effects of land use change explicit through the recognition of different beneficiary groups, value types and spatial locations. We recommend the application of our approach in other contexts, especially in the Global South.

Keywords: disaggregation, ecosystem services, equity, land use change, scenario planning, social-ecological systems

1. Introduction

Human land use is changing in rural areas around the world, and it is not only a key driver of biodiversity loss, but also affects the provision and appropriation of ecosystem services (ES), i.e. the benefits that people obtain from nature (Millennium Ecosystem Assessment 2005; Quintas-Soriano et al. 2016; Díaz et al. 2019). ES research is still heavily focused on assessing aggregated ES provision or aggregated well-being in relation to possible land use options (Rosa et al. 2017; Mandle et al. 2020), but changes and trade-offs in ES provision and appropriation can create winners and losers (Rodriguez et al. 2006; Carpenter et al. 2009; Cord et al. 2017). Unequitable outcomes in ES provision and appropriation can result from, among others, power dynamics, value trade-offs, or spatial dynamics, with implications for distributional, recognitional and procedural equity (Schlosberg 2007; Fraser 2009; Langemeyer and Connolly 2020), as well as for human well-being and sustainable resource use (Leach et al. 2018; Loos et al. 2022).

Scenario planning and analysis of ES provision and appropriation can be useful to anticipate such equity-related effects of land use change, and ES are thus gaining importance as key response variables in scenario analysis (Plieninger et al. 2013; Arkema et al. 2015; Felipe-Lucia et al. 2022). In order to better assess and address equity issues, and to be more relevant to decision-makers, ES research in general, and (ES-based) scenario planning and analysis, should: integrate both ecological and social information (Fischer et al. 2017; Mandle et al. 2020; Felipe-Lucia et al. 2022); include disaggregated analyses of beneficiaries and power dynamics (Oteros-Rozas et al. 2015; Berbés-Blázquez et al. 2016; Rieb et al. 2017); use multi-metric valuation (Rieb et al. 2017; Chan and Satterfield 2020); and recognize multiple scales and locations (Rosa et al. 2017).

However, so far, approaches to ES and scenario research that follow such recommendations remain scarce. To date, many ES assessments are aggregate assessments that continue to overlook the need to disaggregate by dimensions that are clearly relevant to distributional, recognitional and procedural equity (Suich et al. 2015; Cruz-Garcia et al. 2017; Mandle et al. 2020; Brück et al. 2022). Moreover, few ES studies are integrative and combine biophysical and social analyses, especially when it comes to valuation (Chan and Satterfield 2020). When analyzing ES in scenarios, the social component is often overlooked (Rosa et al. 2017; Felipe-Lucia et al. 2022), and scenario analyses that model both ecological and social variables are rare (Felipe-Lucia et al. 2022).

To address these gaps, we present here a generalized, social-ecological approach to support land use decision-making, and its application in a case study in the Global South. Our approach combines scenario planning with disaggregated ES analyses, in order to better address equity issues in the face of plausible trajectories of land use change (Jiren et al. 2020b). We follow a social-ecological approach, understanding social-ecological systems as interdependent and linked systems of people and nature, which are nested across scales (Fischer et al. 2015). Our approach addresses distributional equity issues, by drawing out in a spatially explicit way changes of land use and land cover (LULC), changes in the potential provision of ES, and associated changes of socioeconomic outcomes for different beneficiary groups. The proposed approach also helps to address recognitional and procedural equity issues (Loos et al. 2022). In this way, it can support researchers to provide knowledge on different future trajectories to local people and decision-makers in ways that are useful for planning for the future, while considering equity implications.

Our paper is structured as follows. First, we present a generalized, social-ecological approach to support land use decision-making, with six specific steps to follow, including a justification for each step and potential methods to use. As a second step, we present a case study for how to apply our general approach, in which we draw out the biophysical and socioeconomic implications of four future scenarios for local people and decision-makers in our study area in Ethiopia.

2. A social-ecological approach to support equitable land use decision-making

Different dimensions of ES disaggregation (by beneficiary groups, value types, space; Brück et al. 2022) shed light on different equity issues (distributional, recognitional, procedural; Loos et al. 2022; Leach et al. 2018). Generally, the disaggregation by beneficiary groups is useful in identifying mainly distributional equity issues, but also power issues related to the provision and appropriation of ES (Daw et al. 2011; Felipe-Lucia et al. 2015; Martín-López et al. 2019). Connected to this, the broader social-ecological context of ES provision and appropriation, such as governance or the composition of stakeholders, shape who benefits in which ways, and can reveal important recognitional and procedural equity and power issues (Felipe-Lucia et al. 2015; Martín-López et al. 2019; Jiren et al. 2022). Disaggregation of value types (for example into instrumental, relational and intrinsic values; IPBES 2022) and plural valuation recognize the plurality of values and worldviews, and can contribute to more equitable and environmentally sustainable decisions (Arias-Arévalo et al. 2017; Zafra-Calvo et al. 2020; IPBES 2022). Spatial disaggregation can reveal how ES are provided and appropriated at different spatial scales, and can help reveal distributional equity issues (Hein et al. 2006; Liu et al. 2013; Schröter et al. 2018).

We propose six steps to generate and analyze scenarios of disaggregated, landscape-scale changes in land use as well as ES provision and appropriation (Table 1). These steps are intended to support more equitable decision-making in the context of land use change and ES management. They are (1) Set system boundaries and units of analysis for spatial (dis-) aggregation, (2) Develop narrative scenarios, (3) Translate scenarios into spatially explicit LULC maps, (4) Analyze biophysical changes related to ES, (5) Analyze socioeconomic changes related to ES, and (6) Communicate results for decision-making.

Table 1. Six steps of a generalized, social-ecological approach to support land use decision-making, including a general description of each step, as well as its application and related equity issues and disaggregation dimensions in the case study. We consider distributional, recognitional, and procedural equity issues; we consider disaggregation of ES provision and appropriation by beneficiary groups, value types, and space.

Step and general description (what to do and why)	**Application in Ethiopian case study**	**Equity issues and disaggregation dimensions in the case study**
(1) Set system boundaries and units of analysis for spatial (dis-) aggregation as a basis for further analyses: Identify the landscape and set the system boundaries; consider village or municipality level as a key unit of analysis; use clustering techniques to identify social-ecological archetypes	66 kebeles (smallest administrative units in Ethiopia) within a landscape spanning three districts were identified as meaningful units of analysis, and were clustered into four social-ecological archetypes	Equity: Kebeles as units of analysis and archetypes as a means of aggregation are the basis to make distributional differences explicit (distributional); four different archetypes with differing values and social-ecological contexts (recognitional) Disaggregation: Kebeles of each archetype are in specific locations (space); each archetype is characterized by a specific social-ecological context, and hence represents different groups of beneficiaries (beneficiary groups)
(2) Develop (narrative) scenarios: Define plausible future trajectories through participatory scenario planning; this is the qualitative knowledge basis for quantitative modeling	Participatory scenario planning for 2040 with over 30 groups of local people and stakeholders	Equity: Local stakeholder groups and their perceptions about plausible landscape change are acknowledged (recognitional); knowledge of different stakeholder groups is incorporated into scenarios, which might be used for future policy making (procedural) Disaggregation: Scenario narratives mention all disaggregation dimensions to a certain extent (beneficiary groups, value types, space)

(3) Translate scenarios into spatially explicit LULC maps: Use explicit rules to translate narratives into quantitative assessments of land use change (e.g. agent-based modeling, fuzzy cognitive maps, or Bayesian networks); this is the first step for further quantitative analyses of biophysical and socioeconomic implications	Baseline LULC maps were based on satellite imagery, plus rules for how to modify the baseline map under each scenario, based on the narratives; proximity-based InVEST scenario generator was used to create LULC maps for the four scenarios	Equity/Disaggregation: Spatial distribution of LULC across the landscape is mapped explicitly at kebele and archetype level, for baseline and scenarios (distributional, space)
(4) Analyze biophysical ES changes: Based on LULC data; frequently used methods include the use of causal relationships, extrapolation of ES values from primary data, and regression models; this is the basis for subsequent socioeconomic analyses	Modelling of potential per capita provision of 11 locally important ES, based on the LULC maps derived in step 2, for each kebele, for the baseline as well as the four scenarios	Equity: Choice of ES based on needs of and relevance for local smallholders (recognitional); Spatial distribution of potential provision of ES is made explicit at kebele and archetype level, for baseline and scenarios (distributional) Disaggregation: Spatial distribution of potential provision of ES is made explicit at kebele and archetype level, for baseline and scenarios (space, beneficiary groups)
(5) Analyze socioeconomic ES changes: Further analyze ES provision and appropriation along social, political, economic aspects, based on range of methods for disaggregated ES and stakeholder analysis (e.g. plural valuation, social network analysis); useful for identifying and acknowledging equity and power issues, plurality of values and worldviews	Analysis of three different aspects: degree of ES specialization (based on ES potential provision); importance of four different value types (based on ES potential provision and values ascribed to ES); presence of stakeholder groups with specific interests in local ES	Equity: Degree of specialization as well as value types are made spatially explicit at kebele and archetype level (distributional); beneficiary groups in each kebele archetype and the different value types that they ascribe to ES are recognized (recognitional); analysis of stakeholder presence is a first step towards their consideration in land use decision-making processes (procedural) Disaggregation: Disaggregated analysis of specialization and values by kebele and archetypes (beneficiary groups, value types, space)
(6) Communicate results for decision-making: Re-arrange biophysical and socioeconomic results depending on the related policy question; results should be accessible for locals to develop spatially differentiated polices or strategies	Results were re-arranged to understand how well kebeles of each archetype do on average (with regards to ES potential provision and value types ascribed to ES) at the baseline and in the scenarios, and how variable the outcomes are	Equity: Mean outcomes and their variability are explicit at the archetype level (distributional) Disaggregation: Results at the baseline and for each scenario are (dis-) aggregated to the archetype level (beneficiary groups, space)

2.1 Step 1: Set system boundaries and units of analysis for spatial (dis-) aggregation

The first step is to identify the landscape and set the system boundaries. In this way, following Wu (2013), the approach represents a place-based assessment at the landscape scale in a spatially explicit manner, which helps to understand and improve the dynamic relationship between ES and human well-being in changing landscapes. Once the landscape is identified, choosing meaningful units of analysis is essential for further assessments of land use and ES at different levels of spatial (dis-) aggregation under the scenarios. The village or municipality level can often be a useful unit of analysis, because social and ecological data are often available at this level, and it is usually also the finest scale at which land-use decision-making takes place (Hanspach et al. 2016; Martín-López et al. 2017; Pacheco-Romero et al. 2022). Based on the unit of analysis, clustering techniques can then be used to define social-ecological archetypes (Sietz et al. 2019; Rocha et al. 2020; Pacheco-Romero et al. 2021). Archetypes retain the richness of case studies, while identifying context-sensitive, generalizable patterns that can help to support evidence-based decision-making (Oberlack et al. 2019).

Aggregation into archetypes is especially useful for social-ecological systems, where recurrent patterns of social and ecological phenomena occur across the study area (i.e., relatively homogeneous spatial units that share similar social-ecological characteristics or interactions; Martín-López et al. 2017). The use of such archetypes can help to work with the social-ecological complexity of the study area, and therefore to conduct further assessments, interpret the data, and make results accessible and easier to communicate. This step can address distributional and recognitional equity, mainly through spatial disaggregation (Table 1).

2.2 Step 2: Develop narrative scenarios

The second step is to develop scenario narratives for the chosen landscape through participatory scenario planning (Peterson et al. 2003; Oteros-Rozas et al. 2015). This method engages multiple perspectives of diverse stakeholders, which can potentially reduce power asymmetries and increase the legitimacy of the results, and helps to explore uncertain, but plausible future land use changes (Oteros-Rozas et al. 2015; Jiren et al. 2020b). Narrative scenarios describe qualitative knowledge about land use and ES changes (e.g. key ES relevant to stakeholders, key variables, causal mechanisms and feedbacks that shape overall social-ecological dynamics; Oteros-Rozas et al. 2015; Jiren et al. 2020b; Duguma et al. 2022). Through the participatory process, this step can help to address recognitional and procedural equity, and resulting scenario narratives may refer to multiple disaggregation dimensions with regard to ES provision and appropriation.

2.3 Step 3: Translate scenarios into spatially explicit LULC maps

In the third step, the scenario narratives are translated into spatially explicit, quantitative assessments of land use change and LULC maps. A range of methods can be used here, for example agent-based modeling, fuzzy cognitive maps, or Bayesian networks (Mallampalli et al. 2016). The resulting LULC maps can then be used to quantify, model and map ES (Burkhard 2017; Crossmann 2017; Vihervaara et al. 2017). Producing explicit LULC maps facilitates the comparison of the different scenarios in a spatially explicit way, and provides a sound basis for further quantitative analyses of biophysical and socioeconomic implications (Duguma et al. 2022). However, such translations should be undertaken with care and with attention to biases, and, if possible, in a participatory way, especially since translations of narratives into LULC rules can be fraught with assumptions. This step addresses distributional equity through spatial disaggregation (Table 1).

2.4 Step 4: Analyze biophysical ES changes

Based on the LULC maps, biophysical ES changes can be analyzed. The ES to analyze should best be chosen based on their relevance to local stakeholders, and, if available, using previous research of the study area (Manlosa et al. 2019; Jiren et al. 2020b). The selection of appropriate methods depends on, among others, overall study aims, types of services to map, accuracy required, expected impact in decision-making, mapping skills, and time and data availability (Malinga et al. 2015; Palomo et al. 2017). Frequently used sources of information for ES provision mapping include land cover variables, topographical information and spectral vegetation indices, and frequently used methods include the use of well-known causal relationships between environmental variables, extrapolation of ES values from primary data, and regression models (Martínez-Harms and Balvanera 2012; Burkhard and Maes 2017; Alexis Akakpo et al. 2023). As the basis for all subsequent analyses of socioeconomic changes, biophysical changes in ES provision need to be made spatially explicit. In terms of equity dimensions, this step mainly addresses distributional equity through spatial disaggregation, but also recognitional equity if ES are selected based on local relevance.

2.5 Step 5: Analyze socioeconomic ES changes

Depending on the case study context, further analyses of the social, political, and economic spheres, which are based on biophysical ES changes, can be included. This means to further analyze ES provision and appropriation along the dimensions of beneficiary groups, value types, and space (Brück et al. 2022), for example through further spatial analysis of ES provision (e.g. ES specialization), analysis of governance aspects, or ES valuation based on plural values. Such analyses can be useful for identifying and acknowledging equity and power issues as well as for working with a

plurality of values and worldviews (Reed et al. 2009; Brück et al. 2022). This step can help to address distributional, recognitional and procedural equity issues, through the disaggregation along multiple dimensions.

2.6 Step 6: Communicate results for decision-making

To communicate the biophysical and socioeconomic results, they should be re-arranged and summarized according to specific policy questions. Results should be made accessible for local people and decision-makers to be useful for the development of spatially differentiated polices or strategies to mitigate or encourage specific land use change trajectories (Brück et al. 2022; Duguma et al. 2022). Visualization of data and results is very important, and should consider trade-offs between context-specificity, generalization, and communicability (Harold et al. 2016; Magliocca et al. 2018; Böttinger et al. 2020; Metze 2020). The operationalization of biophysical and socioeconomic results is the last step towards better recognition of distributional, recognitional and procedural equity issues in land use decision-making, through the consideration of multiple dimensions of disaggregation.

3. Case study in southwestern Ethiopia

We applied the general approach outlined above to a case study in southwestern Ethiopia (Table 1). We provide a disaggregated analysis of implications of LULC and connected ES changes under four future scenarios, considering different equity issues and disaggregation dimensions.

3.1 Study area and methods

For Step 1 (Set system boundaries and units of analysis for spatial (dis-)aggregation), we focused on a landscape in southwestern Ethiopia, which is undergoing rapid social-ecological change due to different social, demographic, economic, environmental, technological, political and governance drivers, including population growth, land use and climate change (Jiren et al. 2020b). The study area consists of three woredas (districts), in Jimma Zone, Oromia Region, Ethiopia, namely Gera, Gumay and Setema woreda, which comprise 66 kebeles (the smallest administrative units in Ethiopia). Kebeles in the study area measure on average 30 km^2 and have an average population of approximately 4,000 inhabitants. The landscape is characterized by a mosaic of arable land and pastures, interspersed by woody vegetation, and moist evergreen Afromontane forest (which amounts to roughly 50 % of the current landscape), and is a recognized biodiversity hotspot (Mittermeier et al. 2011; Hylander et al. 2013; Beenhouwer et al. 2016). Local smallholder farmers depend on nature, and ES are locally important for subsistence, income generation and culture (Shumi et al. 2019; Schultner et al. 2021). Livelihood strategies have traditionally been diversified and subsistence-oriented (Manlosa et al. 2019). However, specialization and market integration are strongly encouraged by the government, and many stakeholders expect or even favor such developments (Federal Democratic Republic of Ethiopia, National Planning Commission 2016; Jiren et al. 2020a; Jiren et al. 2020b). Over the past decades, production has begun to shift from subsistence to marketed crops, and access to cash crops with indirect benefits increased (Schultner et al. 2021). Government, non-governmental, private and community-based organizations are present and active in the landscape (Jiren et al. 2022). The governance related to land use and ES management is often strongly hierarchical, and dominated by government administrative organizations (Jiren et al. 2018; Jiren et al. 2022). We chose the kebele level as our minimum unit of analysis, because it is meaningful for local people and decision-makers, and both ecological and social data were available at that level. For more meaningful interpretation and communication of the results, we clustered the 66 kebeles in our study area into four social-ecological, system-specific archetypes, based on nine (current) ecological and social variables, using hierarchical clustering (Duguma et al. 2022).

For Step 2 (Develop narrative scenarios), we conducted participatory scenario planning with over 30 groups of local people and stakeholders, using multiple rounds of workshops between 2015 and

2019. We co-generated four scenarios that plausibly narrate how the landscape might develop until 2040 (Fischer et al. 2018; Jiren et al. 2020b).

For Step 3 (Translate scenarios into spatially explicit LULC), we developed a baseline LULC map based on satellite imagery, and, based on the previously developed narrative scenarios, defined rules for how to modify the baseline map under each scenario. We then used the proximity-based scenario generator of the InVEST software to create LULC maps of the four scenarios (Sharp et al. 2018; Duguma et al. 2022).

For Step 4 (Analyze biophysical ES changes), we selected 11 locally relevant ES (see section on ES selection in the Supplementary Information for details), namely beef, biodiversity, cattle, firewood, honey, khat, maize, plantation coffee, semi-forest coffee, sorghum and teff. We modelled the potential provision of each ES per capita for each kebele at the baseline and in the four scenarios, mainly through regression models, based on the LULC data derived in step 2, as well as additional primary and secondary ecological and social data (see section on ES potential provision in the Supplementary Information for methodological details). We chose per capita measures of ES, because they highlight the amounts that could potentially be appropriated by local people (Spangenberg et al. 2014). Then, the results were re-aggregated and averaged across kebeles for the entire study area, and for each of the four social-ecological archetypes that resulted from step 3, both for the baseline and the four scenarios.

For Step 5 (Analyze socioeconomic ES changes), we chose to analyze three different socioeconomic aspects, namely the degree of ES specialization (which comes with opportunities and risks, e.g. through increased agricultural yield and food productivity, but also through increased vulnerability to ecological and economic shocks, Abson 2019), the types of values ascribed to ES by local people, and the presence of different stakeholder groups in the landscape (governance aspects around ES can have important equity and power implications; Felipe-Lucia et al. 2015). For *ES specialization*, we defined that a kebele was more specialized if its ES provision was more concentrated and less evenly distributed across ES. We calculated the degree of ES specialization through Simpson's index based on adjusted ES potential provision data for each kebele (divided by total kebele area, logarithmic transformation, min-max scaled), at the baseline and for the four scenarios (see section on ES specialization in the Supplementary Information for details). In contrast to the potential provision results above, we adjusted here for total kebele area instead of population, because specialization measures changes with a focus on the landscape level. To analyze the *types of values ascribed to ES* by local people, we used per capita ES provision data (again, highlighting the perspective of local people), and data on four different value types (direct use, exchange, relational, intrinsic) ascribed to ES at the baseline (derived from surveys of 164 local participants). We calculated the importance of the four value types for each kebele, at the baseline and for the four scenarios (see section on value types in the Supplementary Information for details). Finally, we analyzed the *presence of different stakeholder groups with specific interests in local ES* in each scenario and compared them to the baseline, based on stakeholder interviews with the help of space-for-time substitution (selecting four existing landscapes nearby as proxies representing the types of changes described in the four scenarios; Jiren et al. 2022). As in step 4, the results were re-aggregated and averaged for the entire study area and for each social-ecological archetype (except for the presence of different stakeholder groups).

Finally, for step 6 (Communicate results for decision-making), to visualize the results and make them comparable, we took the resulting kebele level data across the baseline and the four scenarios, separately for each aspect of steps 4 and 5 (provision of each ES, specialization, and importance of value types), and split them into seven equally sized groups (only three for stakeholder presence). This resulted in seven categories for each aspect, ranging from "extremely low" to "extremely high", which indicated the relative level of the aspect in a kebele in comparison to all other kebele results across the baseline and the scenarios. We re-aggregated our results further by summarizing ES potential provision and the value types ascribed to the ES. Specifically, we calculated the mean

relative level and its standard deviation across the provision of all ES and the value types for each archetype at the baseline and for each scenario. First of all, this helped to understand how well each archetype did on average at the baseline and in the scenarios, and facilitated an overarching comparison between archetypes (who is better or worse off?). In addition, it allowed to understand how variable outcomes for each archetype were across scenarios, and hence allowed to assess the resilience of each archetype.

3.2 Results

In step 1, based on their baseline characteristics, the 66 kebeles in our study area were clustered into four social-ecological archetypes, namely the accessible-wealthy, the khat-cropland, the pasture-cropland and the woody vegetation archetype (see Figure 1 for a map, Table 2 for short descriptions, Table S1 for a list of all kebeles and their respective archetype; Duguma et al. 2022). Each of these archetypes represented a specific social-ecological context, and hence different groups of beneficiaries, in a spatially explicit way.

Table 2. Social-ecological kebele archetypes and narrative scenarios (adapted from Duguma et al. 2022 and Jiren et al. 2020b).

Social-ecological archetypes	
Accessible-wealthy	12 kebeles with large extents of eucalyptus plantations, relatively accessible and wealthy
Khat-cropland	19 kebeles with distinctly high availability of khat and arable land, located at higher altitudes, with low coffee forest availability and the lowest wealth index
Pasture-cropland	17 kebeles with high availability of pasture and arable land, with the lowest cover of woody vegetation and low levels of coffee forest, khat, and eucalyptus
Woody vegetation	18 kebeles with high extent of woody vegetation cover, high coffee forest availability and high importance of honey production, relatively remote
Narrative scenarios	
Gain over grain: Local cash crops	The scenario was characterized by intensive cash crop production, with large plots of intensively managed coffee, interspersed with khat and tree plantations, which are sold at local, national, and global markets.
Coffee and conservation: Biosphere reserve	In the scenario, a biosphere reserve was established, and the landscape consisted of a mosaic of diversified farmland and forest patches, which combined nature conservation, sustainable agriculture, ecological coffee production, and tourism opportunities.
Mining green gold: Coffee investors	In the scenario, communal lands and forests were transferred to domestic and foreign large-scale coffee investors for the production and export of commercial and specialized coffee.
Food first: Intensive farming and forest protection	The scenario was characterized by industrialized agriculture involving high-yielding varieties and agrochemical inputs, and strictly protected patches of natural forest.

In step 2 and 3, the participatory scenario planning exercise, which recognized knowledge and perceptions of different local stakeholder groups, resulted in four scenario narratives of how the trajectory of the landscape might change by 2040, which were also translated into spatially explicit LULC maps (see Figure 2 for visual representations and LULC maps, Table 2 for short descriptions; Jiren et al. 2020b; Duguma et al. 2022). The four scenarios were named "Gain over grain: Local cash crops", "Coffee and conservation: Biosphere reserve", "Mining green gold: Coffee investors", and "Food first: Intensive farming and forest protection". Generally, the first two scenarios were characterized by integrated land uses, whereas the last two were characterized by segregated land uses and intensification.

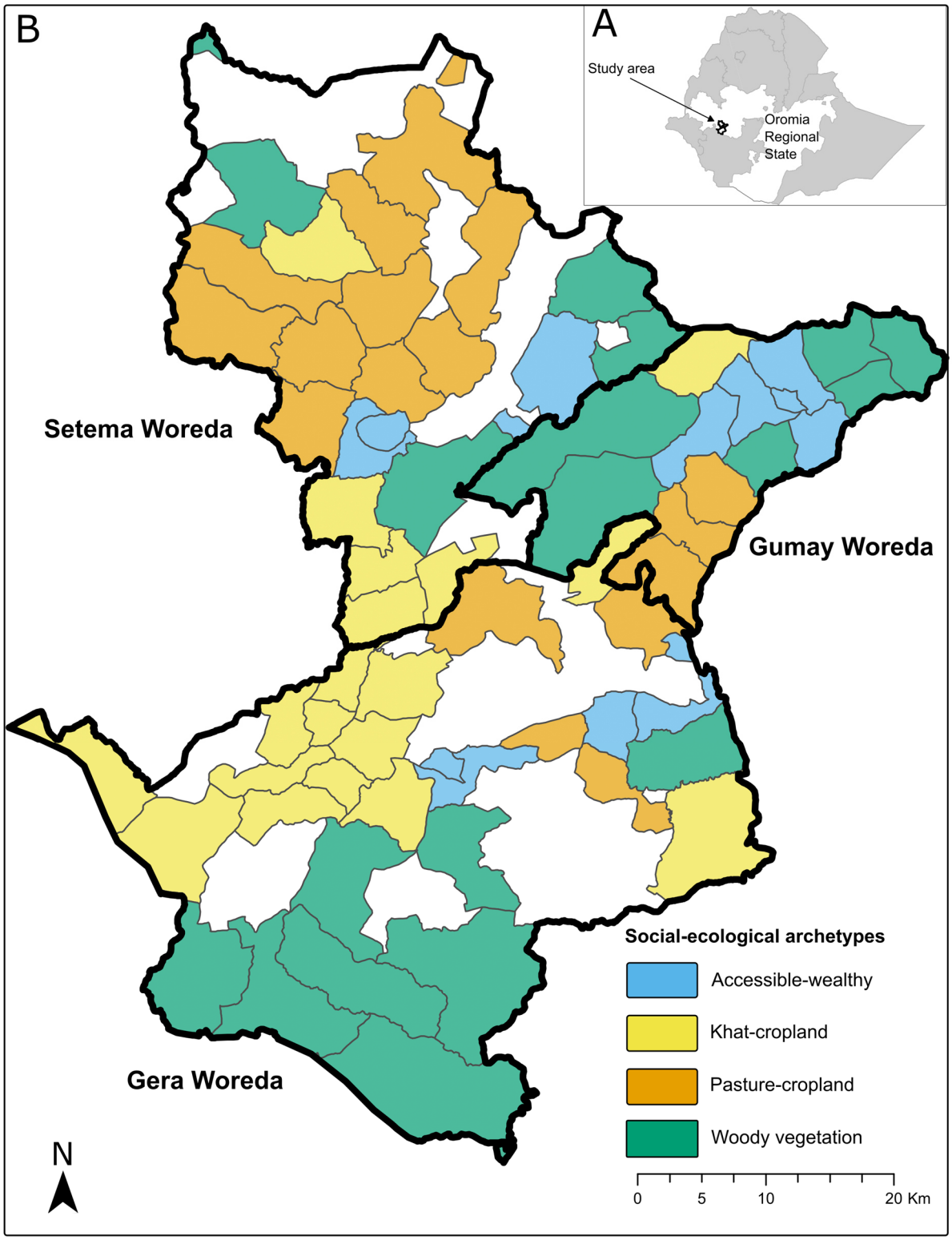

Figure 1. Map of the study area in Oromia regional state in Ethiopia (A). The 66 kebeles (smallest administrative units in Ethiopia) belong to one of four social-ecological archetypes in three different woredas (districts) (B). Kebeles without color are forest kebeles and excluded from the analysis.

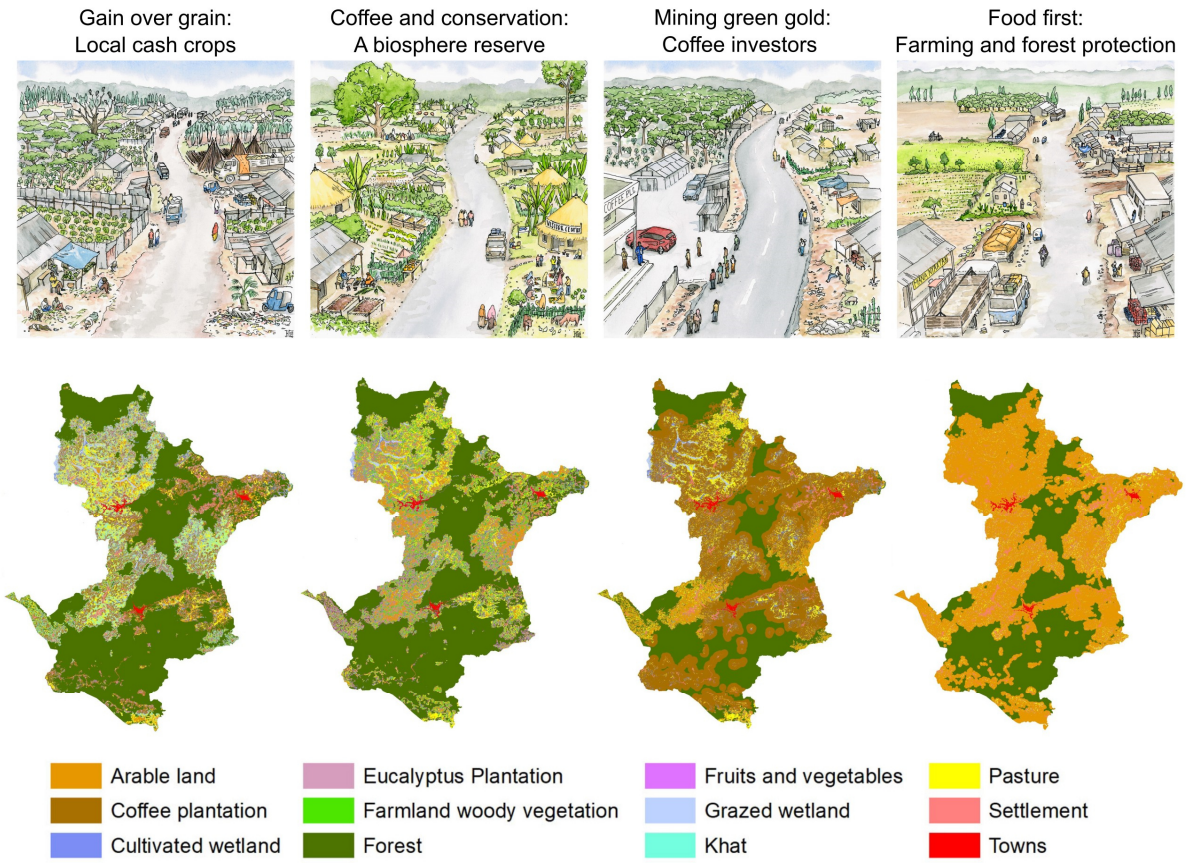

Figure 2. Visual representation of the key features in terms of landscape features and composition in a village, and LULC maps for four future scenarios: (1) Gain over grain: Local cash crops; (2) Mining green gold: Coffee investors; (3) Coffee and conservation: A biosphere reserve; and (4) Food first: Intensive farming and forest protection (adjusted from Duguma et al. 2022 and Jiren et al. 2020b).

In step 4, the level of ES potential provision per capita not only differed between the four scenarios, but also between archetypes (Figure 3; for a more detailed description of the results, see Supplementary Information). For the study area on average (first column in each scenario block), the "Gain over grain" scenario, compared to the baseline, was mostly characterized by increases in the level of potential provision per capita of plantation coffee and khat, at the expense of livestock and cereal crops. Under the "Coffee and conservation" scenario, potential provision of most ES remained the same compared to the baseline, or only changed slightly. The "Mining green gold" scenario showed an increase in plantation coffee, and the "Food first" scenario showed increases in all cereal crops, whereas many other ES decreased.

In contrast to these overall tendencies, the additional analysis by archetype revealed differences in the spatial distribution of potential provision of ES. Whereas observed changes in the archetypes were never opposite (e.g. if an ES decreased under one scenario for the study area on average, we also saw either no change or a decrease for each archetype), potential provision per capita often showed contrasting levels for certain ES under the same scenario, e.g. under the "Gain over grain" scenario, maize was extremely low for the khat-cropland archetype, but high for the woody vegetation archetype. Similarly, under the "Mining green gold" scenario, despite the increase in plantation coffee, the woody vegetation archetype still showed high or very high levels for woody vegetation related ES (semi-forest coffee, biodiversity, firewood, honey), whereas all other archetypes showed lower levels for these ES. Compared to the study area average, the woody vegetation archetype had higher (or the same) potential provision per capita for almost all ES (except for khat and beef) across the baseline and all scenarios. By contrast, the khat-cropland archetype had lower (or the same) potential provision level for almost all ES (except for khat and beef).

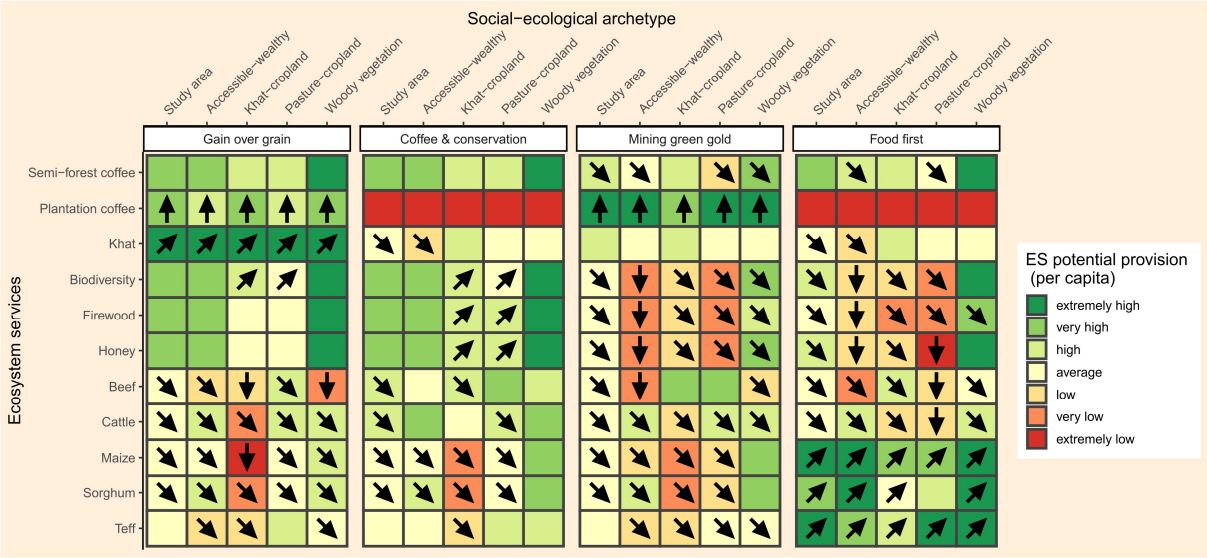

Figure 3. Relative levels of per capita potential provision of 11 locally important ES under four scenarios, for the entire study area and for each social-ecological archetype. To obtain the seven levels, ranging from "extremely high" to "extremely low", kebele level data across the baseline and the scenarios for each ES were split into seven equally sized groups. Arrows indicate changes from the baseline: upward arrow indicates an increase in the relative level of ES potential provision (+6 to +4), diagonal upward arrow indicates a moderate increase (+3 to +1), no arrow indicates no change, diagonal downward arrow indicates moderate decrease (-1 or -2), downward arrow indicates decrease (-3 or -4). For example, under the "Gain over grain" scenario, the level of potential provision of maize per capita for the khat-cropland group is extremely low and has decreased compared to the baseline.

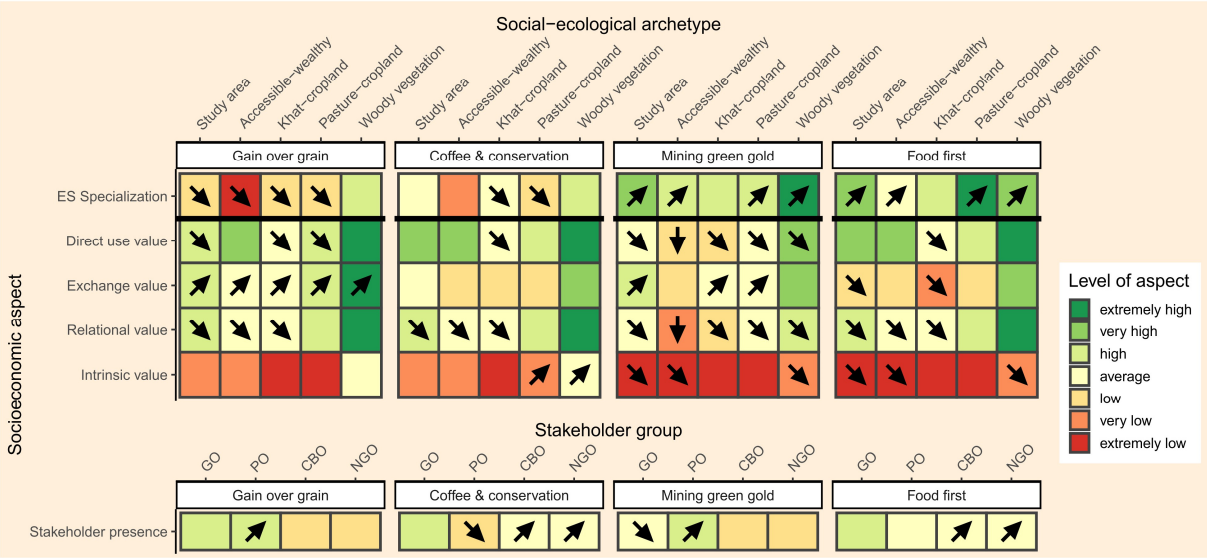

Figure 4. Relative levels of different socioeconomic aspects under four scenarios, for the entire study area and for each social-ecological archetype. To obtain the seven levels, ranging from "extremely high" to "extremely low, kebele level data across the baseline and the scenarios for ES specialization and all value types were split into seven equally sized groups. Stakeholder presence measures the proportions of stakeholder groups at the study area level (GOs = Governmental organizations, POs = Private organizations, CBOs = Community-based organizations, NGOs = Non-governmental organizations), and was only split into three equally sized groups. Arrows indicate changes from the baseline: upward arrow indicates an increase in the relative level (+6 to +4), diagonal upward arrow indicates a moderate increase (+3 to +1), no arrow indicates no change, diagonal downward arrow indicates moderate decrease (-1 or -2), downward arrow indicates decrease (-3 or -4). For example, under the "Mining green gold" scenario, direct use value for the woody vegetation archetype is high, but has decreased compared to the baseline.

In step 5, the three socioeconomic aspects (ES specialization, value types, stakeholder presence) differed between the four scenarios, but also between archetypes (Figure 4; for a more detailed description of the results, see Supplementary Information; for boxplots of specialization and values results see Figures S3 - S6). For the study area on average (first column in each scenario block), ES specialization decreased or remained the same under the two integrated land use scenarios ("Gain over grain" and "Coffee and conservation"), and increased under the two intensification scenarios ("Mining green gold" and "Food first"). For the value types, the "Gain over grain" scenario saw an increase in exchange value, but decreases in direct use and relational value, whereas the "Coffee and conservation" scenario saw almost no changes. The two intensification scenarios were characterized by decreases in almost all value types. In the "Gain over grain" and the "Mining green gold" scenarios, the proportion of private organizations present in the landscape increased, whereas the proportion of community-based and non-governmental organizations increased for the other two scenarios.

In addition, analyzing the socioeconomic aspects by archetype recognized and revealed differences between these four beneficiary groups. Whereas observed changes in the archetypes were never opposite (but instead went in the same direction for all archetypes), socioeconomic aspects showed sometimes contrasting levels under the same scenario, e.g. under the "Mining green gold" scenario, relational value was low for the khat-cropland archetype, but high for the woody vegetation archetype. Again, the woody vegetation archetype and the khat-cropland archetype showed contrasting results. Generally, compared to the study area average, the woody vegetation archetype showed mostly higher-than-average levels for specialization, and higher levels for all value types. By contrast, the khat-cropland archetype had mostly lower specialization levels than the study area average, and all value types were consistently lower or same as average.

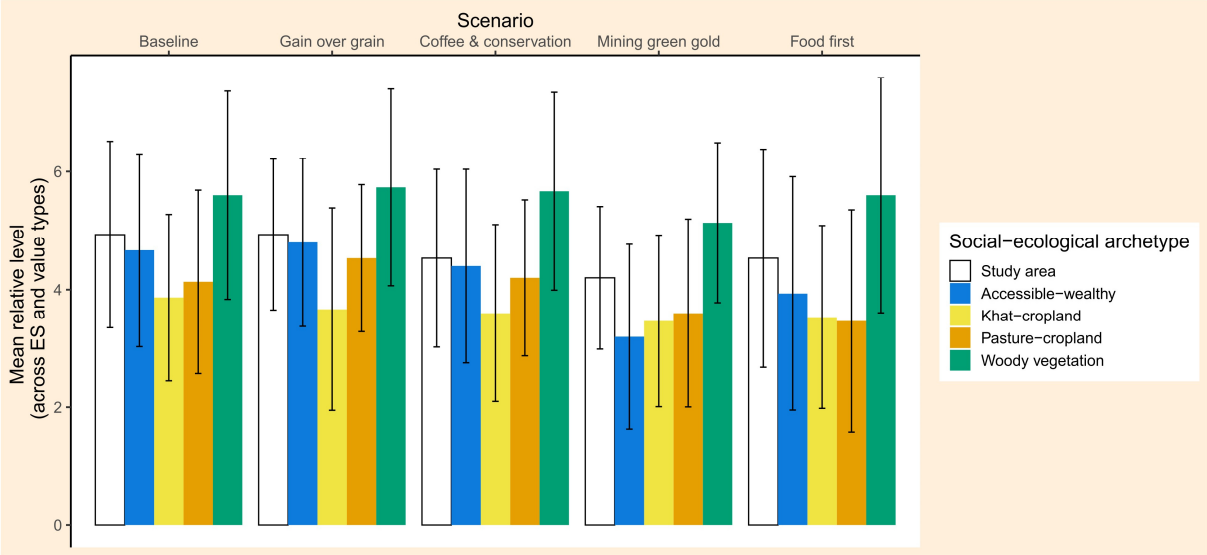

Figure 5. Bar plots of mean relative levels across ES provision and the value types ascribed to them at the baseline and under the four scenarios, for the study area and four social-ecological kebele archetypes, with error bars (based on standard deviations). ES provision is the potential per capita provision of 11 locally important ES; value types include direct use, exchange, relational, and intrinsic value. The heights of the bar plots indicate the mean relative level across ES provision and value types; the error bars indicate the variability of relative levels across ES and value types, based on the standard deviation.

For step 6, at a further level of aggregation (Figure 5), the woody vegetation archetype was again better off than the other archetypes, and showed comparatively high mean relative levels of ES provision and ascribed values. In contrast, the khat-cropland archetype was the relatively worst-off archetype, with comparatively low mean levels at the baseline and under all scenarios. Both the pasture-cropland and the accessible-wealthy archetype did well enough under the two scenarios

with integrated land use ("Gain over grain" and "Coffee and conservation"), but did worse under the two intensification scenarios ("Mining green gold" and "Food first").

4. Discussion and outlook

In this study, we propose a step-by-step approach to facilitate more equitable land use decision-making. Through the recognition of different beneficiary groups, value types and spatial locations, and by bringing together ecological and social data in scenario planning with ES as key response variables (Rosa et al. 2017; Chan and Satterfield 2020), we made equity-related effects of land use change explicit (Schlosberg 2007; Felipe-Lucia et al. 2022), and hence increased the decision relevance of landscape-scale scenarios of land use and ES change (Mandle et al. 2020).

Scenario planning is a useful tool to anticipate effects of land use change in complex social-ecological systems, and, if implemented in a participatory way, can give agency to local people when thinking about potential trajectories of their landscape (Oteros-Rozas et al. 2015; Jiren et al. 2020b). However, the development of scenario narratives on their own may be insufficient to fully understand equity-related effects of land use change, and to meaningfully guide decision-making, and hence needs to be complemented by further analysis of ES provision and appropriation (Rosa et al. 2017; Felipe-Lucia et al. 2022).

Disaggregated analyses of ES provision and appropriation along three dimensions, namely beneficiary groups, value types, and space, can inform more equitable and sustainable decision-making, but such analyses remain rare (Bennett et al. 2015; Mandle et al. 2020). Successful case study examples, similar to our case study, disaggregate ES along several dimensions, generating equity-relevant insights that would not have been possible under an aggregated approach (Dawson and Martin 2015; Arias-Arévalo et al. 2017; Dorresteijn et al. 2017). However, Mandle et al. (2020) found that only a third (31%) of ES assessments disaggregated spatially, and even fewer assessments (7%) disaggregated by beneficiary groups. Our proposed approach opens new opportunities to explicitly recognize different dimensions of disaggregation, namely beneficiary groups, value types and space. Throughout all steps at least one of these dimensions was recognized, and in our application, we disaggregated along these three dimensions in multiple ways: we derived spatially explicit social-ecological archetypes, which represented different beneficiary groups; we recognized different stakeholder groups in the development of scenario narratives; we identified value types as key socioeconomic variables; and we made our results with regard to LULC and ES changes spatially explicit at the kebele as well as the archetype level.

Our social-ecological approach takes ES as key scenario variables, bringing together different types of data and methods for a disaggregated assessment of plausible future land use change. Throughout all steps of the proposed approach, both ecological and social data were required and generated. The application to our case study showed how ecological and social data can successfully be combined to evaluate and present multi-dimensional, disaggregated ES-related outcomes under different future scenarios. For example, ecological and geographical data were used to model ES potential provision, whereas social data were the basis to assess the value types ascribed to ES, or stakeholder presence. We also used different natural and social science methods, such as ecological field surveys, remote sensing, stakeholder interviews and household surveys. Such combination of ecological and social data in ES and scenario analysis has been recommended in the past (Fischer et al. 2017; Mandle et al. 2020; Felipe-Lucia et al. 2022), and has been applied in a range of other case studies, in order to assess equity and sustainability implications of land use change (Pacheco-Romero et al. 2021; Felipe-Lucia et al. 2022; Neyret et al. 2023).

Through the recognition of different beneficiary groups, value types and spatial locations, and by combining ecological and social data, our approach helped to conduct equity-focused analyses of ES under different scenarios. All steps of our proposed approach facilitated the consideration of

distributional, recognitional, and procedural equity issues related to ES. In our case study, we drew out explicitly the equity implications of land use and related ES changes under four plausible trajectories, and thus highlighted winners and losers in terms of biophysical and socioeconomic changes under the different scenarios. Generally, kebeles in the woody vegetation archetype were mostly better off than the other archetypes: they had higher (or the same) potential provision per capita for almost all ES across the baseline and all scenarios, and higher-than-average levels for all value types. However, they showed mostly higher-than-average levels for specialization (specialization may increase vulnerability to ecological and economic shocks due to decreased multifunctionality and resilience, Abson 2019). By contrast, kebeles in the khat-cropland archetype were comparatively worse off: they had lower (or the same) potential provision levels for almost all ES, and all value types were consistently lower or the same as average, but specialization levels were mostly same or lower than the study area average. The other two archetypes were sometimes better and sometimes worse off than the study area average, but they did generally worse under the two intensification scenarios ("Mining green gold" and "Food first"). We also incorporated recognitional and procedural equity through the participatory approach to scenario planning, the recognition of the different kebele archetypes with differing values and social-ecological contexts, and the analysis of stakeholder presence. Similarly, Felipe-Lucia et al. (2022) focused on procedural and distributional equity, and Neyret et al. (2023) on distributional equity related to ES under different landscape management scenarios. We further added to these approaches the component of participatory scenario planning, spatially explicit results of LULC and ES changes, and a focus on the local population through the assessment of the values they ascribed to ES.

Overall, our case study revealed equity-related insights which would not have been derived from a simple aggregated assessment. Therefore, future strategy development by local smallholders and decision-makers needs to be context-specific and inclusive, in order to appropriately mitigate and adapt to future changes. We recommend the application of our approach in other contexts, especially in the Global South, where, similarly to our case study region, people are often closely dependent on nature and also especially vulnerable to change. Depending on the specific case study, the six steps we proposed can be used in a flexible way and be modified, for example through broader application of space-for-time substitution to obtain explicit social data for each future scenario, or by additionally including other-than-local stakeholders in the values assessment.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon request.

Supplementary Information

Methods

R version and packages

All analyses were conducted with the statistical computing language R (R Core Team 2022), R version 4.3.0, using the following R packages: "diverse" (Guevara et al. 2016), "ggpubr" (Kassambara 2020), "sjPlot" (Lüdecke 2022), "performance" (Lüdecke et al. 2021), "sf" (Pebesma 2018), "bestNormalize" (Peterson 2021), "tidyverse" (Wickham et al. 2019), "readxl" (Wickham and Bryan 2023), "ordinal" (Christensen 2022), "glmmTMB" (Brooks et al. 2017).

ES selection

We selected 11 locally important ES, based on previous research, insights from the literature and their relevance in the scenarios. Biodiversity is a supporting ES, which is locally relevant, but also of global importance (Beenhouwer et al. 2016; Duguma et al. 2023). The cereal crops maize (*Zea mays*), sorghum (*Sorghum bicolor*) and teff (*Eragrostis tef*) are the main food crops (Manlosa et al. 2019). Households usually own a small number of livestock, and cattle are used as draft animals and also considered a valuable capital asset (Manlosa, Schultner, Dorresteijn, & Fischer, 2019). We distinguished between cattle used for general purposes versus cattle used specifically for beef fattening (i.e. for meat production). We also included ES stemming from woody plants, which local people largely depend on for different purposes, namely firewood and honey (Shumi et al. 2019). Khat (*Catha edulis,* locally produced stimulant plant) and coffee (*Coffea arabica*), which is either grown naturally and collected in the forest (semi-forest coffee), or grown commercially in plantations (plantation coffee), are the main cash crops in the study area (Manlosa et al. 2019).

ES potential provision modeling

By dividing the total provision by the total population in each kebele, we calculated the per capita provision.

Biodiversity: We used the mean total woody plant species richness at the kebele level as a proxy for biodiversity. We fitted cross-validated generalized linear models for both forest and farmland, relating data on total and forest-specialist woody plant species richness to indicators of human disturbance and environmental conditions, and then projected for the baseline and the four scenarios (Duguma et al. 2023).

Cereal crops (maize, sorghum, teff); livestock (beef, cattle):

To model cereal crops and livestock, we used LM (least squares regression) models based on surveyed kebele data (official data and expert estimates for area of production and total annual production of each kebele; Brück et al. 2023), as well as LULC data and additional geographical data for each kebele (elevation, distance to town, distance to road, woreda; Duguma et al. 2022).

Productivity was calculated as production divided by production area. Distance to road, pasture area, forest area, and total kebele area were log transformed, and all variables center-scaled to improve model estimation.

LM (least squares regression) models were selected for modelling, as these are easier to interpret for expert validation. These were used to relate both current productivity and area of production to the baseline predictor variables. Pearson correlation was used to determine variables that should not be included in the same LM model, as this complicates the interpretation used for model reduction and expert validation. Biplot figures, with the outcome and the predictor variables, were

assessed to identify potentially influential variables and need for quadratics. Plots were also used to determine the likely correct form of the model (e.g. linear, or log-log). Several models were fit for each outcome variable, and compared (using performance::compare_performance). Potential models were then pragmatically selected using principles of forwards and backwards selection, and based on hypothesized and identified influential variables, quadratics, and hypothesized interactions. Final models were selected based on their fit with data, check of model assumptions, and parsimony (fewer variables), as well as a visual check that the models produced sensible outcomes when projected to the current and future landscape scenarios.

Selected models were then projected for both the baseline and the scenarios. Total production was calculated as the estimated productivity times the estimated area of production. This methodology was selected to allow different influences on area and productivity per kebele in a pragmatic and easily interpretable form.

Tried and selected models (for productivity and area of production) for each ES:

The variables:

- Area_arable = area of arable land
- Area_forest = forest area
- Area_pasture = pasture area
- Distance_road = distance from the nearest road
- Distance_town = distance from the nearest town
- Elevm = mean elevation
- ES.py = the productivity of the respective ES
- ES_area = area under production of the respective ES
- Woreda = woreda (Gera, Gumay or Setema)

- Maize model
    - Productivity. Models tested (bold is selected model):
        - lm(maize.py ~ area_arable, data=DF)
        - **lm(maize.py ~ area_arable + poly(elevm,2), data=DF)**
        - lm(maize.py ~ poly(elevm,2) + area_arable + woreda, data=DF)
        - lm(maize.py ~ area_arable + poly(elevm,2) + distance_road + woreda, data=DF)
    - Area of production. Models tested (bold is selected model):
        - lm(maize_area ~ area_arable, data=DF)
        - lm(maize_area ~ elevm + area_arable, data=DF)
        - lm(maize_area ~ elevm*area_arable, data=DF)
        - **lm(maize_area ~ elevm + poly(area_arable,2), data=DF)**
        - lm(maize_area ~ elevm*poly(area_arable,2), data=DF)
- Sorghum model
    - Productivity. Models tested (bold is selected model):
        - lm(sorghum.py ~ area_arable, data=DF)
        - lm(sorghum.py ~ area_arable + elevm, data=DF)
        - lm(sorghum.py ~ elevm + area_arable + woreda, data=DF)
        - lm(sorghum.py ~ area_arable + elevm + distance_road + woreda, data=DF)
        - **lm(sorghum.py ~ elevm + woreda, data=DF)**
        - lm(sorghum.py ~ elevm*woreda, data=DF)
    - Area of production. Models tested (bold is selected model):
        - lm(sorghum_area ~ area_arable, data=DF)
        - lm(sorghum_area ~ poly(elevm,2) + area_arable, data=DF)
        - lm(sorghum_area ~ poly(elevm,2)*area_arable, data=DF)
        - lm(sorghum_area ~ poly(elevm,2) + area_arable + woreda, data=DF)
        - lm(sorghum_area ~ poly(elevm,2)*area_arable + woreda, data=DF)
        - lm(sorghum_area ~ poly(elevm,2) + area_arable + woreda + area_pasture, data=DF)
        - **lm(sorghum_area ~ poly(elevm,2) + poly(area_arable,2) + woreda, data=DF)**

- Teff model
  - Productivity. Models tested (bold is selected model):
    - lm(teff.py ~ elevm, data=DF)
    - lm(teff.py ~ elevm + distance_road, data=DF)
    - lm(teff.py ~ elevm + woreda, data=DF)
    - **lm(teff.py ~ elevm + woreda + area_arable, data=DF)**
  - Area of production. Models tested (bold is selected model):
    - lm(teff_area ~ area_arable, data=DF)
    - lm(teff_area ~ elevm + area_arable, data=DF)
    - lm(teff_area ~ elevm + poly(area_arable,2), data=DF)
    - lm(teff_area ~ elevm*area_arable, data=DF)
    - lm(teff_area ~ elevm*area_arable + woreda, data=DF)
    - lm(teff_area ~ elevm + poly(area_arable,2) + woreda, data=DF)
    - lm(teff_area ~ elevm + area_arable + area_forest + woreda + poly(distance_town,2), data=DF)
    - lm(teff_area ~ elevm + poly(area_arable,2) + woreda + poly(distance_town,2), data=DF)
    - **lm(teff_area ~ elevm + area_arable + woreda + poly(distance_town,2), data=DF)**
- Cattle model
  - Productivity. Models tested (bold is selected model):
    - lm(cattle.py ~ 1, data=DF)
    - lm(cattle.py ~ elevm, data=DF)
    - lm(cattle.py ~ elevm + distance_town, data=DF)
    - lm(cattle.py ~ elevm*distance_town, data=DF)
    - lm(cattle.py ~ distance_town, data=DF)
    - lm(log(cattle.py) ~ 1, data=DF)
    - **lm(log(cattle.py) ~ elevm, data=DF)**
    - lm(log(cattle.py) ~ elevm + distance_town, data=DF)
    - lm(log(cattle.py) ~ elevm*distance_town, data=DF)
    - lm(log(cattle.py) ~ distance_town, data=DF)
  - Area of production. Models tested (bold is selected model):
    - lm(log1p(cattle_area) ~ area_pasture + distance_town, data=DF)
    - lm(log1p(cattle_area) ~ poly(area_pasture,2) + distance_town, data=DF)
    - lm(log1p(cattle_area) ~ poly(area_pasture,2) + distance_road + distance_town, data=DF)
    - lm(log1p(cattle_area) ~ area_pasture * distance_town, data=DF)
    - lm(log1p(cattle_area) ~ area_pasture + distance_town + elevm, data=DF)
    - lm(log1p(cattle_area) ~ area_pasture * distance_town + elevm, data=DF)
    - lm(log1p(cattle_area) ~ area_pasture + distance_town + area_forest, data=DF)
    - lm(log1p(cattle_area) ~ area_pasture * distance_town + area_forest, data=DF)
    - **lm(log1p(cattle_area) ~ area_pasture * distance_town + area_forest + woreda, data=DF)**
- Beef model
  - Productivity. Models tested (bold is selected model):
    - **lm(beef.py ~ 1, data=DF)**
    - lm(beef.py ~ area_pasture, data=DF)
    - lm(beef.py ~ area_pasture + elevm, data=DF)
    - lm(beef.py ~ area_pasture + elevm + distance_town, data=DF)
    - lm(beef.py ~ (area_pasture + elevm + distance_town)^2, data=DF)
    - lm(beef.py ~ area_pasture*elevm*distance_town, data=DF)
  - Area of production. Models tested (bold is selected model):
    - lm(log1p(beef_area) ~ poly(area_pasture,2), data=DF)
    - lm(log1p(beef_area) ~ poly(area_pasture,2) + elevm, data=DF)
    - **lm(log1p(beef_area) ~ poly(area_pasture,2) + elevm + woreda, data=DF)**
    - lm(log1p(beef_area) ~ poly(area_pasture,2) + elevm + woreda + area_forest, data=DF)
    - lm(log1p(beef_area) ~ poly(area_pasture,2) * elevm + woreda, data=DF)
    - lm(log1p(beef_area) ~ area_pasture + elevm + area_forest + woreda, data=DF)
    - lm(log1p(beef_area) ~ area_pasture * elevm + area_forest + woreda, data=DF)
    - lm(log1p(beef_area) ~ poly(area_pasture,2) + elevm + area_forest + woreda, data=DF)
    - lm(log1p(beef_area) ~ poly(area_pasture,2) * elevm + area_forest + woreda, data=DF)

Firewood: We used the mean woody plant species abundance (that provide firewood) at the kebele level as a proxy. Negative binomial models for forest and farmland were based on LULC maps (derived from the narrative scenarios), household survey data on woody plant use, data on woody species distribution collected using ecological field surveys in different land-uses, as well as topographic variables and human disturbance variables generated from LULC maps, and then projected for the baseline and the four scenarios (Duguma et al. Under Review).

Honey: We used the mean woody plant species abundance (that provide bee forage) at the kebele level as a proxy. For modeling, we followed the same approach as for firewood (Duguma et al. Under Review).

Khat: For each kebele, we multiplied khat area at the baseline and in the scenarios (from LULC maps; Duguma et al. 2022) by an average productivity of 0.51 t/ha (reported productivity in Oromia region in 2020/21 for peasant holdings; Central Statistical Agency of Ethiopia 2021).

Plantation coffee: For each kebele, we multiplied coffee plantation area at the baseline and in the scenarios (from LULC maps; Duguma et al. 2022) by an average productivity of 0.926 t/ha (reported productivity in Oromia region in 2020/21 for commercial farms; Central Statistical Agency of Ethiopia 2022).

Semi-forest coffee: We used a series of interlinked models, capturing key production chain nodes of coffee presence, management intensity, and expected yield, parameterized by data from three independent field studies (Shumi et al. 2019; Beche et al. 2022; Zewdie et al. 2022). We projected these for the baseline and the scenarios.

Spatial predictor variables included *elevation*, *slope*, heat load index (*hli*), topographic wetness index (*twi*), *forest type* (a binary variable of whether the forest existed 15 years prior or not), *distance* (from the forest edge), and percent woody vegetation in a 2km radius (*pwv2km*), and *woreda* (Duguma et al. 2022). All variables were examined and transformed if necessary to improve model performance.

To select candidate models, we focused on developing expert-driven, pragmatic (simple) models for each of the components, to be easily interpretable, and minimize the possibility of over-parameterization through the whole model.

Coffee presence was defined as a confirmed location of *Coffea arabica*, including both wild plants and those in managed forest areas, while absence was noted where the surveys did not record a presence. Coffee presence was modeled with a binomial GLM (using stats::glm):

```
glm(formula = coffee_presence ~ poly(elevation, 2) * hli, family = binomial, data = tdata)
```

Coffee management intensity was classified into 6 classes:

- A0: No coffee present, and therefore no management
- A1: Wild forest coffee with low/chance coffee abundance, no management and rarely harvested
- A2: Wild forest coffee with higher coffee abundance, no management and rarely harvested
- B: Wild forest coffee with minimal management (or historical but no current management), and more regular harvest
- C: Managed forest coffee with low-intensity management, including infilling (using local seedlings), pruning, slashing of competing understory, and minor reduction of overstory cover.
- D: Forest-plantation with relatively heavy management of the shade tree level, regular slashing and pruning, infilling (potentially with commercial cultivars), and typically ground-shrub layers aside from coffee removed completely

Coffee management was modeled using a cumulative link model (using ordinal::clm). The model to separate class D from other classes:

> glm(formula = mgmtD ~ invPwv2km * pred_PA * forestType, family = binomial, data = tdata %>% filter(pred_PA > 0))

The model for management class:

> ordinal::clm(formula = management_type2 ~ distance + pred_PA * W_NAME + pred_D, data = tdata %>% filter(pred_PA > 0))

Coffee yield was observed during fieldwork for all three included studies and was modelled using a zero inflated mixed model (using glmmTMB::glmmTMB):

> glmmTMB(log1p(yield) ~ invPwv2km + pred_mgmt2_b * W_NAME + (1|datasource), ziformula = ~ pred_mgmt2_b * invPwv2km, data = tdata %>% filter(pred_PA>0))

We used deterministic model versions to predict the expected yield as:

> EY[i] <- (probability of coffee presence > 0.5) * (1 – probability of yield absence) * (prediction of yield given presence)

The interlinked models were evaluated relative to the input data, and then projected to the baseline and the scenarios. To project the models, landscape rasters were aggregated to a cell size of 100m x 100m (1ha) using the mode for categorical and mean for continuous variables, extracted landscape variables from forest areas only, transformed these based on the transformation and polynomial models developed above, predicted outcomes via *nimble*, and converted back into raster format for further processing.

ES Specialization

We divided total potential provision of each ES in each kebele by total kebele area. We then log transformed the data to account for right skewed distributions, and normalized to [0, 1] through min-max scaling across the baseline and all scenarios for each ES. We then calculated the degree of ES specialization through Simpson's index (for infinite samples) based on the adjusted potential provision data across all ES in each kebele, at the baseline and under the four scenarios (gini.simpson.C in R package diverse, v0.1.5, Guevara et al. 2016; Brück et al. 2023).

Value types

Through a survey with 164 local participants in two kebeles of each archetype, we assessed the mean importance ascribed to 11 ES within four value types (direct use, exchange, relational, intrinsic; Brück et al. Under Review in People and Nature). We did not collect data on plantation coffee, since it is currently not present in the landscape. Instead, based on the scenario description for the "Mining green gold" scenario (Jiren et al. 2020), we assumed high exchange values ascribed to it by local people, because they earn an income through employment in plantations (highest other mean exchange value is 5.89 for semi-forest coffee, so we assumed an exchange value of 6 for plantation coffee), whereas all other value types were assumed to be zero, because local people cannot directly use or relate to it. For each kebele, at the baseline and the scenarios, we multiplied the level of ES potential provision per capita in septiles (-3 to 3) by these ascribed values for each ES, and then summed across ES for each value type.

Results

Table S1. Kebeles of the study area and their social-ecological archetypes.

Kebele	Archetype	Kebele	Archetype
Awisa Bilo	Woody vegetation	Sika	Woody vegetation
Bara Enchni	Pasture-cropland	Sogesecha	Pasture-cropland
Berarigo	Woody vegetation	Solako	Pasture-cropland
Bereguda	Woody vegetation	Susatela	Pasture-cropland
Berwerenigo	Pasture-cropland	Tinibachale	Khat-cropland
Bore Dedo	Pasture-cropland	Toba Town	Accessible-wealthy
Bore Gogo	Khat-cropland	Tuma Teso	Woody vegetation
Boricho Deka	Woody vegetation	Wala	Woody vegetation
Chanido	Pasture-cropland	Wanija Kerisa	Accessible-wealthy
Chefeta Yera	Pasture-cropland	Wegecha	Khat-cropland
Chira Town	Accessible-wealthy	Yasera Pera	Woody vegetation
Demu Kufi	Pasture-cropland		
Difo Mani	Woody vegetation		
Done	Pasture-cropland		
Dora Ongo	Khat-cropland		
Doradocha	Khat-cropland		
Duseta	Khat-cropland		
Efyacgi	Accessible-wealthy		
Gatira Town	Accessible-wealthy		
Gatokure	Accessible-wealthy		
Gebakoro	Khat-cropland		
Gedagute	Khat-cropland		
Gela	Pasture-cropland		
Gemina Dacho	Woody vegetation		
Genida Chala	Accessible-wealthy		
Gere Ifalo	Woody vegetation		
Gesecha	Pasture-cropland		
Gido Bere	Woody vegetation		
Gina Chola	Khat-cropland		
Gurariso	Woody vegetation		
Gure Dako	Khat-cropland		
Guribodage	Woody vegetation		
Kecha Anideracha	Pasture-cropland		
Kele	Woody vegetation		
Kesebedado	Khat-cropland		
Kola Kinibibit	Khat-cropland		
Kola Suja	Pasture-cropland		
Komibolicha	Khat-cropland		
Kuba Toba	Khat-cropland		
Kubo Silech	Pasture-cropland		
Kuda Kefo	Accessible-wealthy		
Kudakunacho	Woody vegetation		
Lima Tad	Accessible-wealthy		
Masano	Khat-cropland		
Muje	Khat-cropland		
Nego Agu	Khat-cropland		
Oba Toli	Woody vegetation		
Sata Gona	Pasture-cropland		
Secha	Khat-cropland		
Sed Loya	Accessible-wealthy		
Sedu	Pasture-cropland		
Seta	Khat-cropland		
Setema Kecha	Accessible-wealthy		
Sheni Chemere	Woody vegetation		
Shoni Belira	Accessible-wealthy		

Detailed description of the results (Figure 3)

For the study area on average (first column in each scenario block), potential provision per capita was extremely high for khat in the "Gain over grain" scenario, for plantation coffee under the "Mining green gold" scenario, and for maize and teff under the "Food first" scenario. It was extremely low for plantation coffee under all scenarios, except the "Mining green gold" scenario. Potential provision per capita showed the biggest increase from the baseline for plantation coffee under the "Mining green gold" scenario, closely followed by the increase in plantation coffee under the "Gain over grain" scenario, whereas the biggest decreases were observed for beef and cattle under the "Gain over grain" scenario, for woody vegetation related ES and livestock under the "Mining green gold" scenario, and for firewood and livestock under the "Food first" scenario.

With regard to the kebele archetypes, potential provision per capita showed sometimes contrasting levels for certain ES under the same scenario, e.g. under the "Food first" scenario, honey was extremely low for the pasture-cropland archetype, whereas they were high and extremely high for the woody vegetation archetype. However, observed changes in the archetypes were never opposite, meaning that if an ES decreased under one scenario for the study area on average, we saw either no change or a decrease for each archetype, but never an increase (and vice versa).

In the woody vegetation kebele archetype, potential provision per capita was extremely high for woody vegetation related ES (semi-forest coffee, biodiversity, firewood, honey) at the baseline, and under all scenarios except "Mining green gold"; for khat under the "Gain over grain" scenario for all archetypes; for plantation coffee under the "Mining green gold" scenario for all archetypes except khat-cropland; under the "Food first" scenario, for biodiversity, honey and all cereal crops for the woody vegetation archetype, for maize and sorghum for the accessible-wealthy archetype, for teff for the pasture-cropland archetype. Potential provision per capita was extremely low for plantation coffee for all archetypes under the "Coffee and conservation" and "Food first" scenarios; for maize for the khat-cropland archetype under the "Gain over grain" scenario; for semi-forest coffee and honey for the pasture-cropland archetype under the "Food first" scenario. We observed the biggest increase from the baseline for plantation coffee under the "Mining green gold" scenario (closely followed by "Gain over grain") for all archetypes, and the biggest decrease for the accessible-wealthy archetype for woody vegetation related ES (biodiversity, firewood, honey) under the "Mining green gold" scenario.

Variation between kebeles within the same archetype was generally low, but moderate variation was observed for khat and teff for some of the archetypes, and for the woody vegetation archetype for few ES, whereas semi-forest and plantation coffee partly showed high variation (Figure S1).

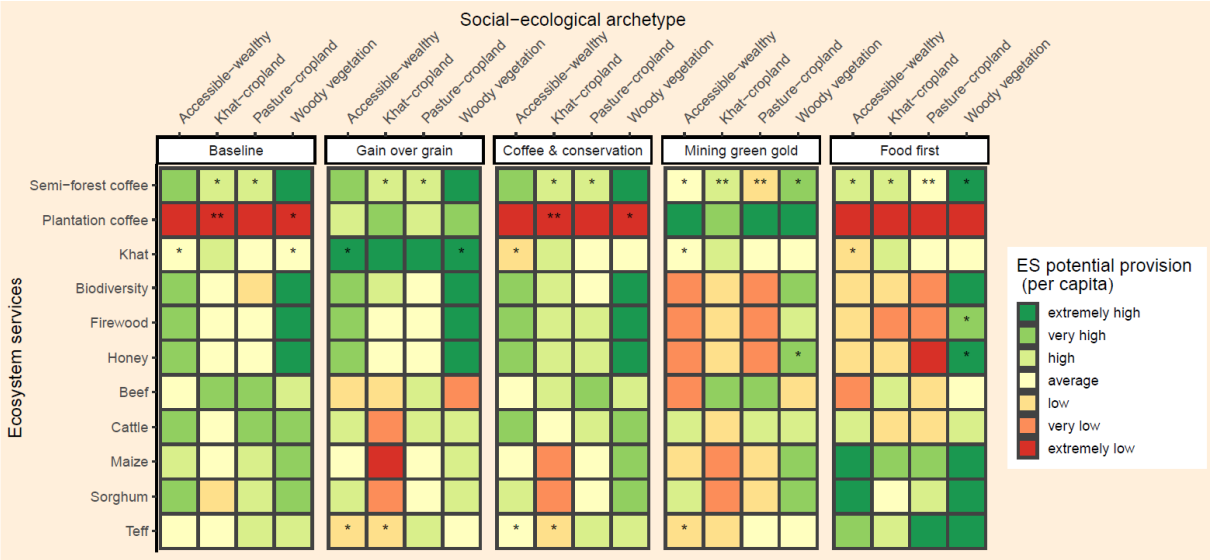

Figure S1. Relative levels of per capita potential provision of 11 locally important ES at the baseline and under four scenarios, and variation between kebeles within the same archetype. Variation was calculated through the coefficient of variation (standard deviation divided by mean) based on per capita provision of each ES across kebeles within each archetype. Coefficient of variation results across all ES and archetypes were then split into three equally sized intervals, indicating low, moderate (*) and high (**) variation.

Detailed description of the results (Figure 4)

For the study area on average (first column in each scenario block, Figure 4), intrinsic value was extremely low under the "Mining green gold" and the "Food first" scenario. ES specialization showed the biggest increase under the "Mining green gold" and the "Food first" scenarios, whereas the biggest decreases arose for direct use and relational value under the "Mining green gold" scenario.

Under the same scenario, we sometimes observed contrasting levels of one aspect for different archetypes. Observed changes in the archetypes were never opposite, meaning that if an aspect decreased under one scenario for the study area on average, we saw either no change or a decrease for each archetype, but never an increase (and vice versa).

ES specialization was extremely high for the woody vegetation archetype under the "Mining green gold" scenario, and for the pasture-cropland archetype under the "Food first" scenario. Specialization was extremely low under the "Gain over grain" scenario for the accessible-wealthy archetype. For the woody vegetation archetype, direct use and relational value were extremely high at the baseline and under all scenarios (except "Mining green gold"), as well as exchange value under the "Gain over grain" scenario. Intrinsic value was extremely low for almost all archetypes under the two intensification scenarios. Specialization showed the biggest increase for the accessible-wealthy archetype under the "Mining green gold" scenario and for the pasture-cropland archetype under the "Food first scenario", and the biggest decrease was observed for the khat-cropland archetype under the "Gain over grain" scenario. The accessible-wealthy archetype showed the biggest decreases for direct use and relational value under the "Mining green gold" scenario.

The variation between kebeles within the same archetype was generally low, but moderate variation was sometimes observed, whereas intrinsic value partly showed high variation (Figure S2).

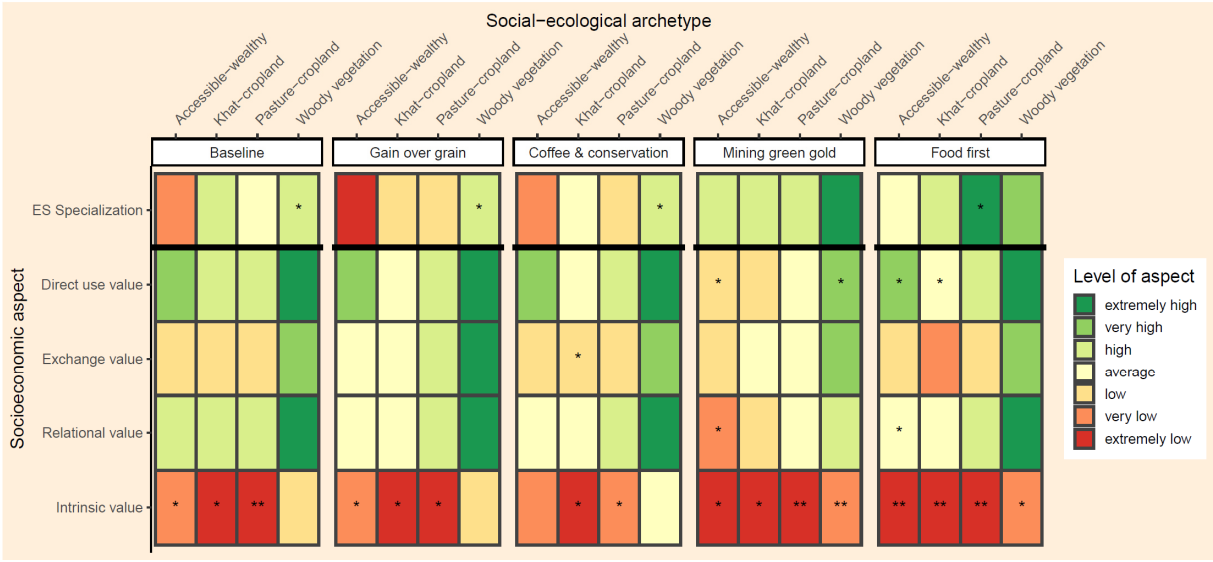

Figure S2. Relative levels of different socioeconomic aspects at the baseline and under four scenarios (ES specialization, direct use value, exchange value, relational value, intrinsic value), and variation between kebeles within the same archetype. Variation was calculated through the coefficient of variation (standard deviation divided by mean) based on specialization and value type data across kebeles within each archetype. Coefficient of variation results across all archetypes were then split into three equally sized intervals, indicating low, moderate (*) and high (**) variation.

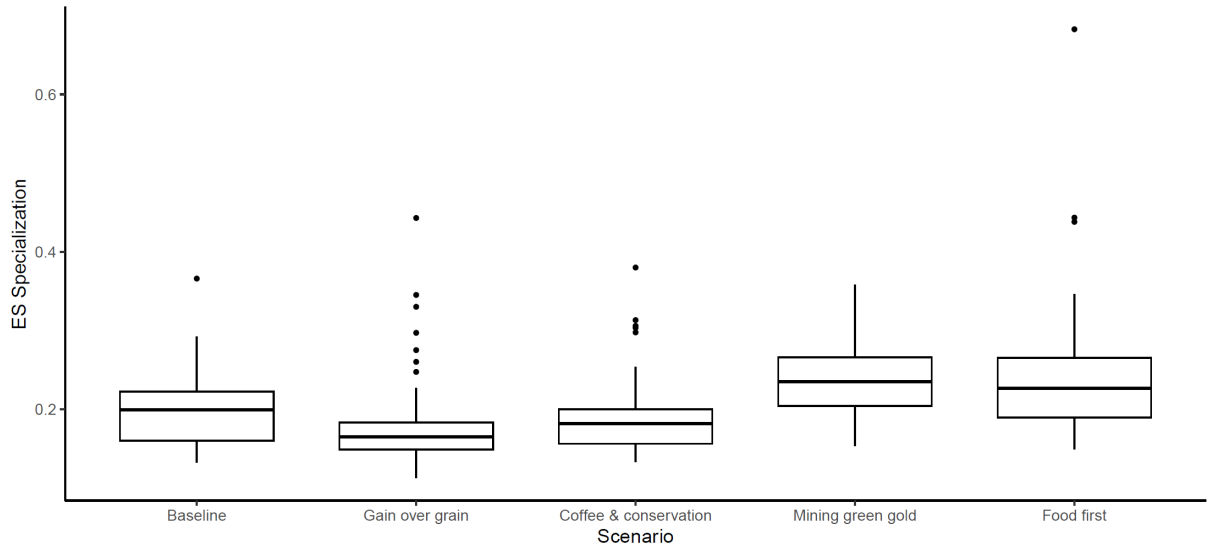

Figure S3. Boxplots of ES specialization at the baseline and for the four scenarios, across 66 kebeles.

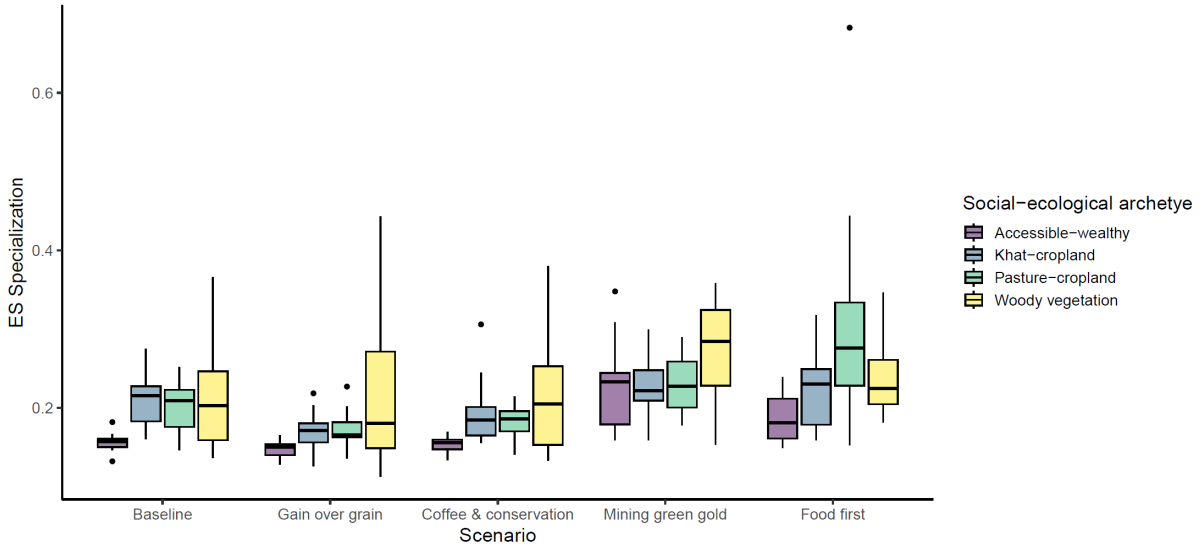

Figure S4. Boxplots of ES specialization at the baseline and for the four scenarios, across 66 kebeles, by social-ecological archetypes.

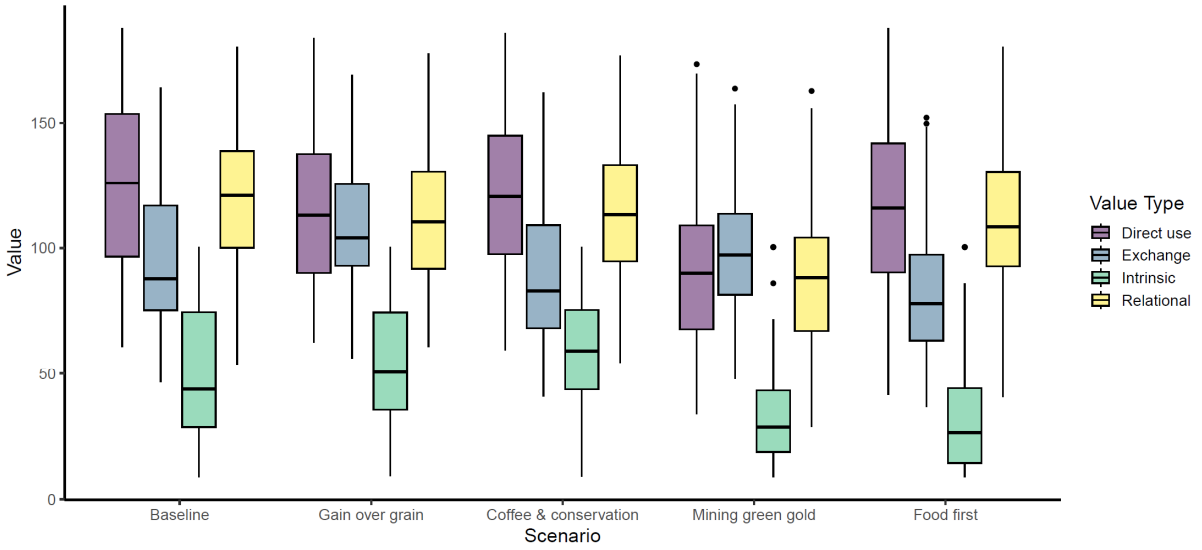

Figure S5. Boxplots of value importance at the baseline and for the four scenarios, across 66 kebeles, by value types.

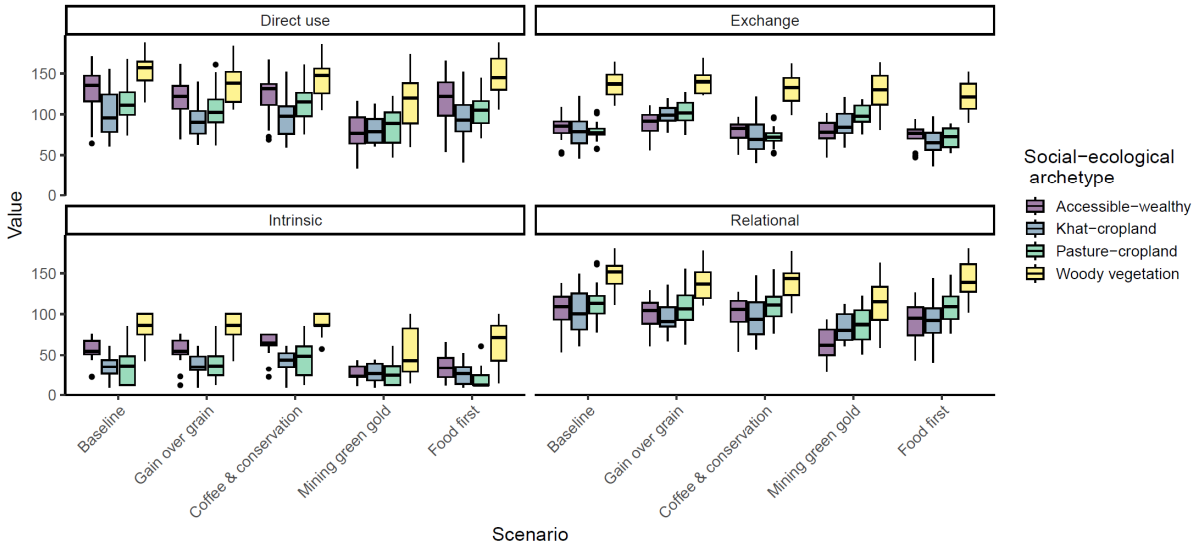

Figure S6. Boxplots of value importance at the baseline and for the four scenarios, across 66 kebeles, by value types and social-ecological archetypes.

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Appendix

Additional publications

The below co-authored publication (Appendix I) and the policy booklet (Appendix II) were created as part of ETH-Coffee project in the same case study region as the empirical chapters of this dissertation. They thus provide additional valuable insights and background information to this dissertation.

Appendix I: Duguma, D. W., **M. Brück**, G. Shumi, E. Law, F. Benra, J. Schultner, S. Nemomissa, D. J. Abson, and J. Fischer. Future ecosystem service provision under land-use change scenarios in southwestern Ethiopia: *Under Review in Ecosystems and People.*

In this paper, the spatial distribution of six ES (erosion control, carbon storage, coffee production, crop production, livestock feed, and woody plant biodiversity) was modelled and mapped for the current landscape and the four scenarios. The results show distinct LULC and ES changes across the scenarios, provide valuable input for decision-makers and stakeholders, and could help to identify sustainable land use options. Modelling of ES potential provision has already been a part of Chapter V of this dissertation, but this paper goes into more detail (presenting spatially disaggregated results at the kebele level) and includes additional ES (erosion control and carbon storage).

Appendix II: Jiren, T. S., D. J. Abson, **M. Brück**, J. Fischer, and J. Hanspach. 2023. *A shared vision for the landscapes of southwestern Ethiopia*, Sofia. [online] URL: https://books.pensoft.net/books/13390.

This booklet reports the outcomes of efforts to identify a widely shared, common vision for the future of the landscapes within Jimma zone in 2040. Local stakeholders developed a common vision for the future of their landscape, which was synthesized via 10 interacting key principles. Stakeholders also identified key transformative strategies to achieve the transition towards the desired future landscape. Although stakeholders largely agreed on the key principles, some disagreements on their implementation remained, mainly with regard to agricultural development and land tenure security. Formulating a vision for a desirable future landscape is only the beginning, but it can be a starting point for tangible steps towards actually achieving the collectively formulated vision. This policy booklet not only summarized the common vision for the case study region, but also incorporated results of the entire ETH-Coffee project, thus acting as a communication tool of the project research results targeting local stakeholders. It illustrates what local stakeholders envision for their landscape, and can thus act as a tool to contrast and compare with the modelled results for the four scenarios in Chapter V.

Appendix I: Future ecosystem service provision under land-use change scenarios in southwestern Ethiopia

Dula W. Duguma, Maria Brueck, Girma Shumi, Elizabeth Law, Felipe Benra, Jannik Schultner, Sileshi Nemomissa, David J. Abson, Joern Fischer

Under Review in Ecosystems and People

Future ecosystem service provision under land-use change scenarios in southwestern Ethiopia

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Abstract

Continued pressure and transformation of land-use by humans are key drivers of biodiversity and ecosystem services (ES) loss. To determine the sustainability of possible future land-use practices, it is important to anticipate likely future changes to biodiversity and ES. This can help stakeholders and decision-makers to understand and assess the viability of current development policies and design alternative future pathways. Focusing on a biodiversity hotspot in southwestern Ethiopia, we considered four future land-use scenarios (namely: 'Gain over grain', 'Coffee and conservation', 'Mining green gold' and 'Food first' scenarios) that were developed via participatory scenario planning. We modelled and mapped the spatial distribution of six ES (erosion control, carbon storage, coffee production, crop production, livestock feed, and woody-plant richness) for the current landscape and the four scenarios. Our results show distinct land use and land cover (LULC) changes across the scenarios – forest cover (approximately 50% of the baseline landscape) would remain similar in the 'Gain over grain' and 'Coffee and conservation' scenarios, but decreased by approximately half in the 'Mining green gold' and 'Food first' scenarios. Smallholder farmers specializing on cash crops ('Gain over grain' scenario) would likely cause little change to ES generation, but major losses in ES would result from intensification scenarios ('Mining green gold' and 'Food first'). Finally, the 'Coffee and conservation' scenario appears to be the most sustainable scenario because it would secure diverse ES for the long term. Our findings provide valuable input for decision-makers and stakeholders, and could help to identify sustainable land-use options.

Keywords: ecosystem service, landscape, land-use scenarios, large-scale intensification, modeling, spatial mapping

1. Introduction

Continued pressure and transformation of land-use by humans are key drivers of the loss and degradation of both biodiversity and ecosystem services (ES) (Sala et al. 2000; Foley et al. 2005; Díaz et al. 2019). Quantifying and understanding land-use change and its spatiotemporal dynamics is critical in tackling sustainability challenges (Winkler et al. 2021). To determine the sustainability of future land-use practices, it is important to identify plausible future changes that could help stakeholders and decision-makers to understand and assess the implications of current development policies and design alternative future pathways. Specifically, analyzing the effects of future land-use change on ES could contribute to improved decision-making related to ecological and human wellbeing that are fundamental to sustainable development (Schirpke et al. 2020).

Land-use models can support societal visioning processes by sketching out the spatially explicit outcomes of alternative management objectives and quantifying the synergies and tradeoffs associated with land-use change (Verburg et al. 2015; Bürgi et al. 2022). Typically, maximization of provisioning ES generated from intensively managed agricultural landscapes has been found to be negatively correlated with the provision of other types of ES and biodiversity conservation, indicating strong trade-offs (e.g., Raudsepp-hearne et al. 2010; Seppelt et al. 2013; Schirpke et al. 2020). In contrast, less-intensified agricultural landscapes aim to minimize this trade-off through a spatially integrated production of provisioning ES and other ES or biodiversity conservation (Fischer et al. 2013; Kremen 2015; Mehrabi et al. 2018).

Land-use changes vary geographically. For instance, while increases in forest cover and cropland abandonment are major drivers of land-use change in parts of Europe, deforestation and agricultural expansion are major drivers in the global south (Hua et al. 2018; Winkler et al. 2021; Meyfroidt et al. 2022). As in many countries in the global south, in Ethiopia, agricultural landscapes provide multiple ES that directly contribute to the livelihoods of local people, but are under constant pressure from population growth, deforestation, tenure insecurity, forest land grabbing, land-use conflicts, and large-scale land transfers to investors (e.g., Taddese 2001; Rahmato 2011; Rodrigues et al. 2021). Rapid land-use change is threatening these landscapes and their ES multifunctionality, which is crucial for human well-being (Rasmussen et al. 2018; Shumi et al. 2019a). Different studies have attempted to analyze the impact of LULC change on ES based on historical and current spatial datasets (Tolessa et al. 2017; Abera et al. 2021). However, an outlook into the future to understand possible changes in ES in Ethiopia is still lacking. This gap can be addressed by using social-ecological land-use scenarios (hereafter land-use scenarios) generated through participatory scenario planning.

Participatory scenario planning – in which scenarios are co-designed with local stakeholders – captures local realities based on the knowledge of stakeholders (Peterson et al. 2003; Henrichs et al. 2010). Comparative scenario analysis then provides a rational and reflected basis for improved decision-making and for exploring alternative development pathways and policy options (Alcamo et al. 2008; Henrichs et al. 2010). For our study, we used four land-use scenarios (namely: 'Gain over grain', 'Coffee and conservation', 'Mining green gold' and 'Food first' scenarios – a brief summary of each scenario is given in methods section) developed for southwestern Ethiopia via participatory scenario planning (Jiren et al. 2020). In a first step, the narrative scenarios were translated into spatially explicit maps by Duguma et al. (2022). In this contribution, we build on these maps and analyze the potential supply of six ES under the different scenarios of land-use change – one supporting service (woody-plant richness), two regulating services (erosion control and carbon storage), and three provisioning services (coffee production, crop production, and livestock feed).

Our approach involved mapping the spatial distribution of the potential supply of these ES for the current landscape as well as for the four land-use scenarios in order to understand the effect of land-use change on potential ES. We use the term "potential supply of ES" to mean the full potential of ecological functions or biophysical elements within the ecosystem, which is broadly

comparable to natural capital stocks (Martinez-Harms and Balvanera 2012; Burkhard et al. 2014; Vihervaara et al. 2017). We analyzed changes at the landscape scale and at the level of the smallest administrative unit in Ethiopia (the "kebele" level), which is an important social-ecological unit for land-use planning. The kebele level is where government policies are implemented, and where development agents work with communities for activities such as soil and water conservation or tree planting (Wiegant et al. 2022). Kebeles in our study area typically contain approximately 500 households (Rodrigues et al. 2018; Duguma et al. 2022) and have an average area of approximately 30 km2. Comparing the outcomes of ES under alternative land-use scenarios can help to evaluate management strategies and identify desirable and undesirable impacts that could benefit or harm both people and ecosystems. As such, the findings can be useful input for local stakeholders and decision-makers.

2. Methods

2.1 Study area

Our study focused on a landscape in southwestern Ethiopia (Fig. 1), which is part of the Eastern Afromontane biodiversity hotspot (Mittermmeier et al. 2011), and the origin of coffee Arabica (Senbeta and Denich 2006). The landscape is dominated by smallholder farmers whose dominant economic activities and livelihoods are dependent on subsistence farming, coffee production, livestock production, and forest based ESs (Tadesse et al. 2014b; Schultner et al. 2021; Shumi et al. 2021). The study area has undulating topography ranging between approximately 1200 and 3000 m above sea level.

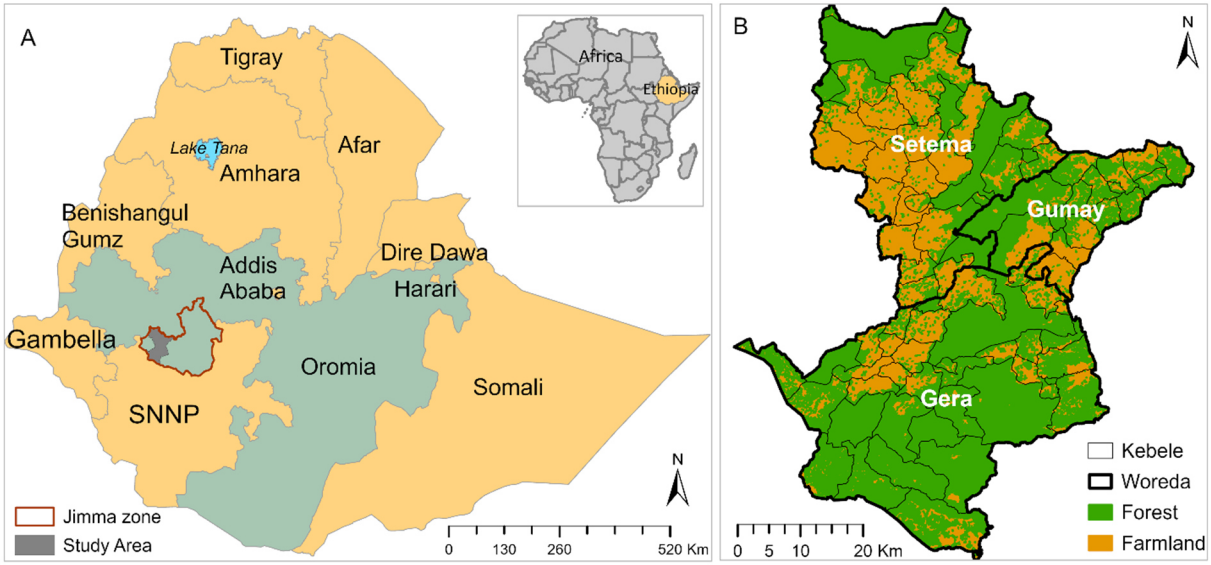

Figure 1. (A) the study area in Jimma Zone (grey), Oromia region (green grey) within Ethiopia (other regions are tan-colored); (B) the district boundaries (woredas; delimited by a thick black line and labelled in white) and lower administrative boundaries (kebeles; thin black lines) in the study area. The underlying land cover map illustrates the distribution of forest and farmland (adapted from Duguma et al. 2022).

2.2 The scenarios

Spatially explicit scenario maps were produced by translating participatory narrative scenarios developed for the year 2040 into land-use maps (Jiren et al. 2020; Duguma et al. 2022). The scenarios were entitled 'Gain over grain', 'Mining green gold', 'Coffee and conservation' and 'Food first', and are briefly summarized below in Table 1.

Table 1. Brief summaries of social-ecological scenarios for southwestern Ethiopia for the year 2040 (for details see Jiren et al. 2020; Duguma et al. 2022).

Scenario	Description
'Gain over grain': Local cash crops	This scenario prioritizes smallholder farmers' specialization and commercialization to boost development focused on cash crops such as coffee, the stimulant drug khat (*Catha edulis*), and fast-growing trees on available farmland and without expanding into the forest. The production of food crops is limited: little space remains for cultivating cereal crops, and few farmers maintain small cereal fields in the most fertile land. Incomes increase for some households, but inequality also increases, and traditional institutions collapse.
'Coffee and conservation': Biosphere reserve	This scenario is based on a more balanced land-use approach and best-practice sustainable resource management that combines sustainable agriculture, environmentally friendly coffee production, and tourism. The landscape is a diversified mosaic of forest and farmland; livestock production and communal grazing take place much like at present, and people grow fruit, vegetables, and grains. Aggregate profits generated are modest, but social capital and cultural integrity are high.
'Mining green gold': Coffee investors	This scenario is characterized by the intensification and specialization of coffee production through large investors who use modernized production approaches with high external inputs. Smallholder land, communal land, and forests conducive for coffee investment have been transferred to capital investors for the creation and expansion of coffee plantations. Local farmers are left to farm marginalized areas unsuitable for large-scale coffee plantations. Social injustice increases and local and traditional knowledge is being lost.
'Food first': Intensive farming and forest protection	This scenario is driven by climate change making coffee production less viable, and by food production failing elsewhere in the country. Large amounts of food are now produced in the focal landscape through intensive, large-scale agriculture, which involves land consolidation, the clearing of woody vegetation, and the expansion of cropland into available flat areas and wetlands. Remaining patches of natural forest are strictly protected. Social injustice increases, and local and traditional knowledge are eroded.

2.3 LULC mapping

For the current landscape (baseline), we mapped six main LULC classes from 10-meter resolution Sentinel-2 satellite imagery using supervised image classification (Duguma et al. 2022). The main land-use land cover classes identified were woody vegetation, arable land, pasture, cultivated wetland, grazed wetland, and settlement. These thematic classes were further refined into 12 classes using additional criteria such as slope, farmland heterogeneity, altitude, and distance from the forest edge. Using these additional criteria, we refined our LULC classes and added coffee plantations, eucalyptus plantations, khat, and fruits and vegetables. Woody vegetation was classified into forest (patches > 1 ha) versus farmland woody vegetation (patches < 1 ha). The additional land cover classes were created to match the land-uses that emerged from the participatory scenarios. To generate plausible future land-use maps, we used the baseline map together with translation rules and the InVEST proximity based scenario generator (Sharp et al. 2018) (for details, see Duguma et al. 2022). All spatial processing and analysis (such as classification, mapping) outlined in this manuscript was undertaken using ArcGIS Pro.

2.4 Quantifying and mapping ES

There are several ways of quantifying and mapping ES (e.g., Costanza et al. 1997; Maes et al. 2012; Martinez-Harms and Balvanera 2012). We focused on the measurement of ES in biophysical units, because our goal was to map and quantify the potential supply of ES rather than specific benefits or values associated with ES. We understand that the benefits and values of ES can provide useful additional information for decision-makers (e.g., Bagstad et al. 2013; Boerema et al. 2017; Vihervaara et al. 2017), however, modeling potential supply is a necessary first step.

We focused on six ES: woody-plant richness (a supporting ES), erosion control and carbon storage (two regulating ES), and coffee production, crop production, and livestock feed (three provisioning ES) (Table S1). For each ES, we modelled its biophysical potential for the baseline and for each of the four scenarios. We chose these ES based on spatial data availability (e.g. in relation to LULC data or a Digital Elevation Model (DEM)), and taking into account the main changes in the different scenarios. We did not include specific cultural ES because of a lack of data availability; but we note that traditional cultural ES for the local community are often closely related to the occurrence of woody-plants (Megerssa and Kassam 2020; Shumi et al. 2021). Studies elsewhere also showed that cultural ES are correlated with supporting services (e.g., Raudsepp-hearne et al. 2010; Turner et al. 2014). Changes in woody-plant richness therefore may also indicate possible changes in at least some traditional cultural services like ritual celebration or as cultural flagship species (Megerssa and Kassam 2020).

Erosion control

To map erosion control, we used InVEST 3.8.2 software from the Natural Capital Project (Sharp et al. 2018). The Sediment Delivery Ratio (SDR) of the InVEST model is similar to the Revised Universal Soil Loss Equation model (Sharp et al. 2018; Sahle et al. 2019; Abera et al. 2021). We used SDR to estimate avoided erosion export, which specifically shows the contribution of vegetation to keeping soil from eroding from each pixel. Briefly, the SDR model draws on the input parameters DEM, rainfall erosivity, soil erodibility, LULC, and biophysical information related to LULC that is containing a crop management factor (C) as well as possible support practices (P) (data sources for each input variables are indicated in Tables S2, S3 and S4). Details of how the InVEST SDR model works are described in the model documentation (Sharp et al. 2018).

Carbon storage

To map carbon storage, we used the InVEST Carbon Storage and Sequestration model – which uses maps of LULC along with stocks in four carbon pools (aboveground biomass, belowground biomass, soil and dead organic matter) to estimate the amount of carbon currently stored in a landscape (Sharp et al. 2018; Sahle et al. 2019; Benra et al. 2021). Data on carbon pools were collected from areas that have similar characteristics to our study region, mostly in other parts of southwestern Ethiopia (Table 2). The InVEST model aggregates the amount of carbon stored in these pools according to land-use maps to estimate the net amount of carbon storage potential of each scenario (Sharp et al. 2018; Sahle et al. 2019).

Woody-plant richness

Woody-plant species were surveyed in 72 farmland sites and 108 forest sites in 20 m x 20 m quadrants (Shumi et al. 2018, 2019b). From this dataset, total woody-plant species richness (hereafter woody-plant richness) was calculated, modelled using baseline predictor variables, and spatially projected for the entire study area for the baseline and scenario conditions (Duguma et al. 2023). We used the mean value of these spatially predicted maps for woody-plant richness. Woody-plant richness constitutes a useful proxy of supporting ES because a lot of biodiversity in southwestern Ethiopia is directly linked to native tree diversity (Tadesse et al. 2014b; Schultner et al. 2021; Shumi et al. 2021). Moreover, woody-plant richness could also be an indirect indicator of cultural services, because different trees and shrubs are valued by the local people in ritual celebration, as symbolic features, or as cultural flagship species (Megerssa and Kassam 2020).

Table 2. Carbon pools (tonnes/ha) used for LULCs. (Abbreviations: c_above = above ground carbon, c_below = below ground carbon, c_soil = carbon in soil, c_dead = carbon in dead organic matter).

LULC	c_above	c_below	c_soil	c_dead	References
Arable land	1.82	0.0455	108	0	(Abera et al. 2021)
Coffee plantation	123	40	25	6	(Mohammed and Bekele 2014; Tadesse et al. 2014a)
Cultivated wetland	2	2	7.5	2	(Abrha 2018)
Eucalyptus plantation	128	20	101	5	(Mohammed and Bekele 2014; Tadesse et al. 2014a)
Farmland woody vegetation	151	51	111	10	(Abera et al. 2021)
Forest	243	45	163	0.03	(Abera et al. 2021)
Fruits and vegetables	4	5	120	0	(Abegaz et al. 2020)
Grazed wetland	15	35	74	4	(Abegaz et al. 2020)
Khat	3.1	0.8	55	0	(Betemariyam et al. 2020; Getnet and Negash 2021)
Pasture	15	35	75	4	(Vanderhaegen et al. 2015; Abegaz et al. 2020)
Rural settlement	8	8	20	2	(Abera et al. 2021)
Towns	5	5	15	2	(Abera et al. 2021)

Crop production

To quantify and map crop production, first, we identified the three most important crops in the landscape through fieldwork – these were teff, maize, and sorghum (Manlosa 2019). Second, we used the latest productivity data (Table S5) available for the three crops in the study area (Central Statistical Agency (CSA) 2018; Belachew et al. 2022) and weighted each of the crop productivities based on the number of field plots collected for 72 randomly selected households (Manlosa 2019) (i.e., teff accounted for 42% of fields, and so was assigned a productivity weight of 0.42, maize accounted for 29%, and sorghum 15%) to get weighted crop productivity. Third, we multiplied the weighted productivity by area of arable land (i.e., cropland) in each kebele for the baseline and scenarios respectively to estimate total crop production for each kebele.

Coffee production

Similar to crop production, coffee production was also estimated at the kebele level based on LULC maps. For the baseline landscape, we used coffee productivity estimates (Table S5, Central Statistical Agency (CSA) 2018), which represents productivity values for smallholder farmers. This was also used for the projection of coffee productivity for three scenarios in which coffee continued to be grown by smallholders ('Gain over grain', 'Coffee and conservation', and 'Food first'). For the 'Mining green gold' scenario, we used estimates of coffee productivity from existing coffee plantations within our study region (Zewdie et al. 2022). Coffee productivity remained constant between 2011 to 2020 (Belachew et al. 2022). Hence, we also assumed no increase in coffee productivity in the scenarios. Coffee production per kebele was estimated by multiplying the potential coffee area of a given kebele (forest within coffee altitude or coffee plantation) with coffee productivity.

Livestock feed

We used area of grazing land in hectares as a proxy for livestock feed following (Kandziora et al. 2013). Grazing land is the most important source of livestock feed in this region contributing to about 80 % of the feed (Negassa et al. 2013). This pragmatic assumption is required as reliable estimates of cattle production per hectare do not exist for the study region. We acknowledge that this simple measure has limitations. Most notably, even though grazing land (pastures and grazed wetlands) are the main cattle grazing areas in all seasons, local communities also use fallow crop

fields and sometimes forest to graze livestock. There is, however, no reliable data available on this, and we reasoned that the most important source of livestock feed was very likely easily measurable grazing land.

2.5 Changes of ES under scenarios

First, we summarized the values of each ES at the landscape level (i.e. entire study area) for each scenario. We used the sum of values for erosion control, carbon storage, crop production, coffee production and livestock feed, and the mean for woody plant richness. For each ES, we subtracted the baseline value from the values of the scenarios to analyze their impact. Second, we analyzed changes in ES at the kebele level, because landscape-wide changes in ES potential may not be uniform across all kebeles. To quantify changes at the kebele level, we first extracted and summarized the values of ES for the current and future scenarios. We then divided the respective values of each ES by the total area of the respective kebele to obtain a measure of each kebele's relative ES potential. For woody-plant richness, we did not use the sum of values (because site-level richness values cannot be added meaningfully) but instead used the mean of predicted values across all grid cells within a given kebele. For further analysis and presentation (e.g. for correlation analysis), we transformed and center-scaled ES for the current landscape and scenarios.

2.6 Correlation analysis

Correlation analysis is the most widely used method to examine relationships between ES (e.g., Qiu and Turner 2013; Spake et al. 2017; Vallet et al. 2018). Here, correlations among potential ES were carried out using non-parametric Spearman's rank correlation (r) at kebele level. As all of our ES have a metric in which larger values are more desirable, positive correlations indicated a synergetic relationship between two services (e.g., Bennett et al. 2009; Raudsepp-hearne et al. 2010; Spake et al. 2017), whereas negative correlation indicated a trade-off relationship (Qiu and Turner 2013; Spake et al. 2017).

3. Results

3.1 Land cover changes

Currently, forest, arable land and pasture account for approximately 53%, 26% and 11% of the study area, respectively. Changes in these figures are very diverse among the scenarios (Table 3; Fig. S1; Duguma et al. 2022). In 'Gain over grain', forest cover did not change compared to the baseline (53%), the currently negligible extent of coffee plantations expanded to 12%, while arable land contracted to just 9%. In 'Mining green gold', coffee plantations covered almost half the landscape (49%), while forest covered shrunk to 26%. In 'Coffee and conservation', the extent of forest cover remained unchanged, but farmland woody vegetation increased to 10% of the landscape. In 'Food first', forest cover decreased to 35%, while arable land increased to 57% of the landscape.

3.2 ES changes

ES changes differed strongly across the scenarios (Table 4). In 'Gain over grain' and 'Coffee and conservation', woody-plant richness, erosion control, carbon storage and coffee production increased; while crop production and livestock feed decreased. In 'Mining green gold', coffee production more than doubled, while all other ES decreased. Similarly, in 'Food first', crop production more than doubled but the other five ES decreased.

Table 3. Percentage (%) of LULC for the current landscape and land-use scenarios. The values in the table are in percent.

Land cover	Current landscape	'Gain over grain'	'Coffee and conserva-tion'	'Mining green gold'	'Food first'
Arable land	26.5	9.3	12.3	9.4	57.4
Coffee plantation	0.3	12.3	0.3	49.1	0
Cultivated wetland	4.9	4.6	4.6	4.9	0
Eucalyptus plantation	0.1	6.4	0	0	0.1
Farmland woody vegetation	1.7	1.5	9.8	0.7	0
Forest	52.9	52.8	52.9	26.4	35.2
Fruits and vegetables	0.1	0.1	8.6	0.1	2.1
Grazed wetland	0.9	0.9	0.9	0.9	0
Khat	0.1	6	0.1	0.1	0.1
Pasture	11.1	4.2	8.5	6.6	3.3
Settlement	1.3	1.3	1.3	1.3	1.3
Towns	0.3	0.6	0.6	0.6	0.6
Total (%)	100	100	100	100	100

Table 4. Percentage change of ES potentials for each scenario in relation to the current landscape. Positive values indicate an increase and negative values indicate loss of potential ES provision. Changes in woody-plant richness denote changes in mean species richness, while changes in other ES are based on changes in the sums of a given ES across the entire study area. Units of absolute values are indicated for the baseline (SPR = mean woody-plant species richness, Mgt = Mega tonnes, t = tonnes, and ha = hectares). For scenarios, units are percentage changes relative to the baseline.

		Percentage change (%)			
ES potentials	Current land-scape	'Gain over grain'	'Coffee and conserva-tion	'Mining green gold'	'Food first'
Woody-plant richness	10 SPR	3.88	9.37	-33.28	-21.55
Erosion control	3,868 Mgt	1.18	0.83	-0.9	-1.82
Carbon storage	81 Mgt	6.33	6.17	-18.16	-21.04
Coffee production	52,211 t	87.93	75.89	297.58	-0.01
Crop production	209,323 t	-55.54	-45.76	-54.45	208.71
Livestock feed	33,853 ha	-57.56	-21.96	-37.57	-72.97

ES changes were not uniform across the landscape (Fig. 2, Fig. S2). For instance, in 'Gain over grain', woody-plant richness remained unchanged for many kebeles; the mean increase in erosion control was very heterogeneous across kebeles; and crop production decreased for almost half of the kebeles. A similar pattern was apparent for 'Coffee and conservation', with the addition that woody-plant richness increased in many kebeles to various extents. For 'Mining green gold', coffee production showed strong increases in most kebeles. Despite a decrease in erosion control and carbon storage at the landscape level in this scenario, both of these ES in fact increased in several kebeles (Fig. 2). For 'Food first', the increase in crop production was very heterogeneous across kebeles, as was the decrease in other ES.

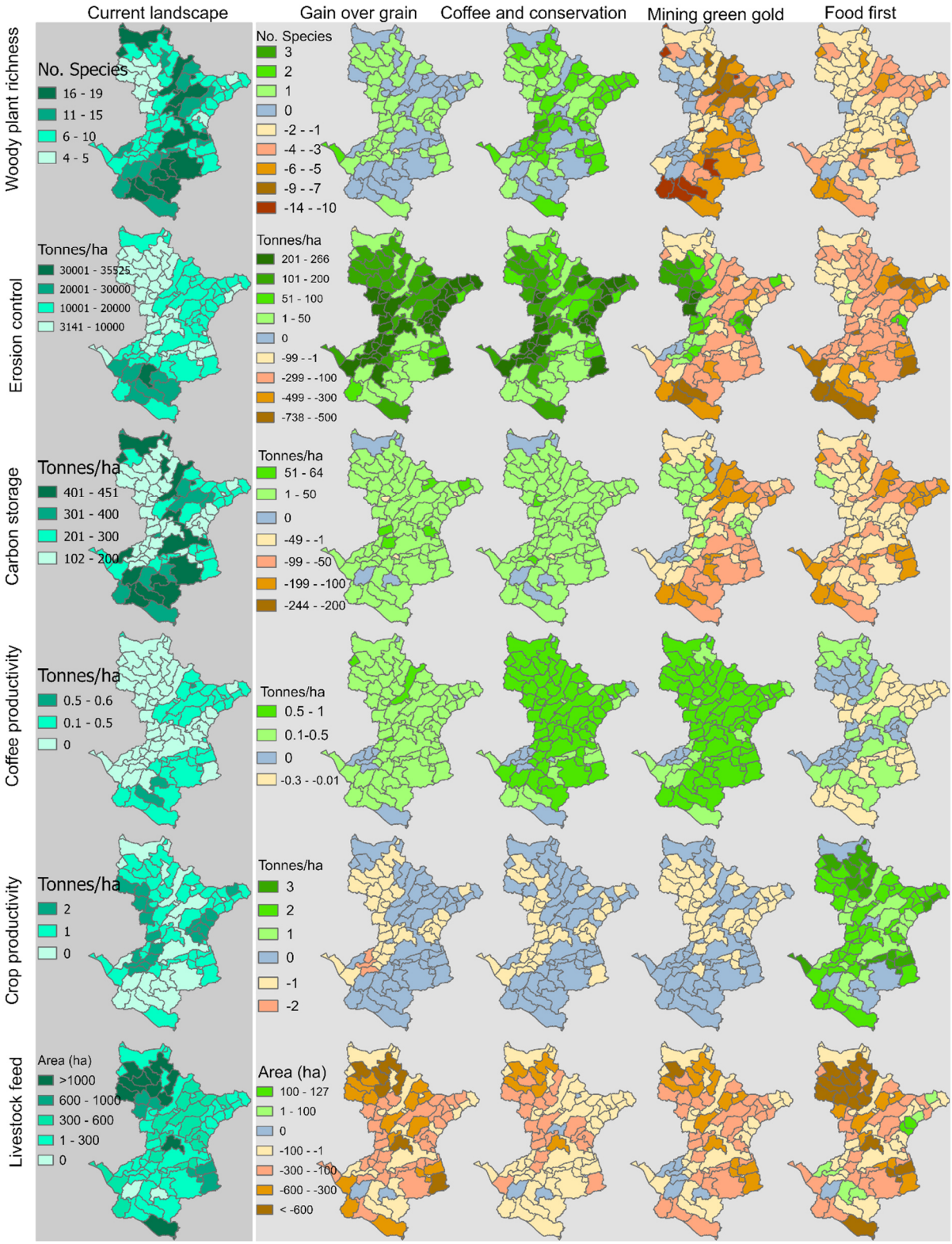

Figure 2. Potential ES maps and changes at the kebele level. The left column shows current ES potentials. The other columns show changes for the scenarios. Orange shades in the right panel indicate a decrease in a given ES, whereas green shades indicate an increase; blue indicates no change relative to the baseline in a given ES. Class boundaries were defined using manual classification for visualization purpose and for comparison across the scenarios for individual potential ES. Absolute values of potential ES for each scenario are shown in Fig. S2.

3.3 ES synergies and tradeoffs

ES synergies and tradeoffs varied only slightly across the scenarios. ES relationships in the current landscape, 'Gain over grain', 'Coffee and conservation' and 'Food first' were very similar. Here, synergies occurred between woody-plant richness, erosion control, carbon storage, and coffee production; and these showed tradeoffs with crop production and livestock feed (Fig. 3). For 'Food first', crop production showed a very strong trade-off with coffee production, carbon storage, erosion control, and woody-plant richness, and livestock feed showed no correlation with erosion control. For 'Mining green gold', the correlation analysis revealed different patterns. Coffee production showed almost no correlation with woody-plant richness, erosion control, and carbon storage.

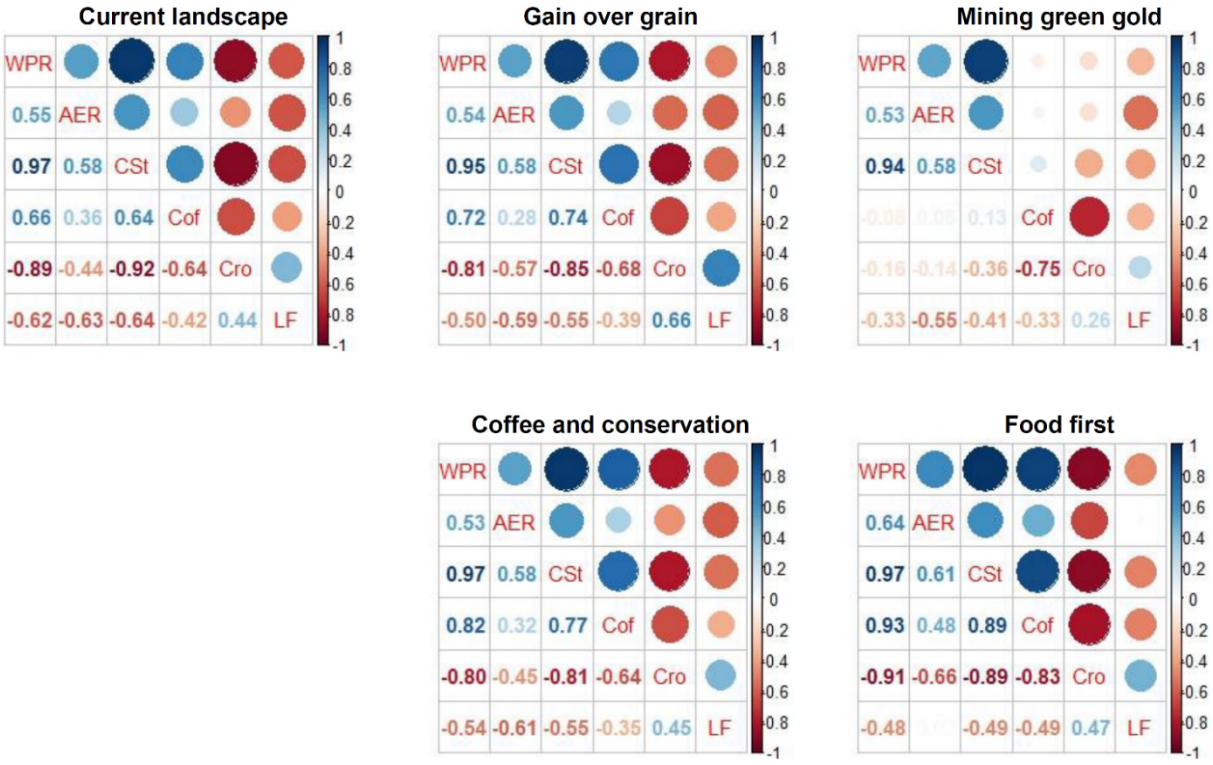

Figure 3. Correlation analysis showing tradeoffs and synergies between ES under the current landscape and scenarios. (Abbreviations: WPR = Woody-plant richness, AER = Avoided erosion, CSt = Carbon storage, Cof = Coffee production, Cro = Crop production, and LF = Livestock feed). Blues in the graph indicate synergies and Reds indicate trade-offs.

4. Discussion

4.1 Change in ES under scenarios

Our findings show that changes in potential ES provision were strongest for land-use scenarios involving large-scale agricultural intensification, whether through food crops or cash crops. Smallholders specializing on cash crops within existing farmland (i.e., the 'Gain over grain' scenario), in contrast, would likely cause less impact on potential ES compared to the 'Mining green gold' and 'Food first' scenarios. Moreover, the 'Coffee and conservation' scenario was associated with relatively positive changes on potential ES provision, and may also be more beneficial to the local community and resilience of the environment than the other scenarios. Below we briefly highlight the present context of landscape change and discuss the implications of each scenario in detail.

4.1.1 Current context of landscape change

The current landscape consists of a mosaic of forest and farmland, where forest patches (>= 1ha) and farmland each cover approximately 50% of the landscape (Table 3, (Duguma et al. 2022)). The rural population heavily depends on locally generated provisioning ES (Ango 2018; Schultner et al. 2021; Shumi et al. 2021), and prefers integrated agroecosystem management (Jiren et al. 2018) – with possible benefits for both people and ecosystems (Altieri 2008; James et al. 2023). However, research findings in the study area shows that smallholder farmers are shifting towards cash crops (Dharmendra Kumar et al. 2014; Gebrehiwot et al. 2016; Jaleta et al. 2016), partly because of persistent problems with crop raiding (Ango et al. 2014; Dorresteijn et al. 2017). At the same time, incidences of small and medium scale forest grabbing for coffee plantation have increased (Tadesse et al. 2014b; Ango 2018). Furthermore, since 2005, Ethiopian government policy in general has been encouraging large-scale agricultural intensification to increase food security and availability (Keeley et al. 2014; Bachewe et al. 2018; Moreda 2018). With this current landscape context in mind, in the following, we discuss the implications of our land-use scenarios for environmental conservation and human wellbeing.

4.1.2 'Gain over grain'

In addition to increases in cash crop production (such as eucalyptus, coffee, and khat), this scenario could also provide slight increases in other ES such as erosion control (by 1%), carbon storage (6%), and woody-plant richness (4%) (Table 4). Such increases could be beneficial even beyond the landscape, for example because they help to control soil loss, avoid downstream siltation, and maintain a productive local microclimate. All of these benefits directly stem from the increase in cash crop plantation, combined with the preservation of woody vegetation and forest extent. Coffee plantations under this scenario were expanded on arable land and pasture within suitable altitude ranges for coffee in the future (Moat et al. 2017; Duguma et al. 2022); whereas khat and eucalyptus were grown mostly at high altitude kebeles and on steep and degraded arable land (Jiren et al. 2020; Duguma et al. 2022). However, decreases in crop production (by about 55%) and livestock feed (57%) could have very significant negative impacts on the local community, likely impacting dietary diversity, nutritional values, and cultural values (Wayessa 2020; Kim et al. 2022).

Our results are consistent with research findings from elsewhere. For instance, in China, the Gain For Green Program (GFGP) tree plantation (mainly monocultures of eucalyptus, bamboo, Japanese cedar) played key role in land cover change, and led to the conversion of approximately 23% of cropland in Southwestern China to tree plantations between 2000-2015 (Hua et al. 2018). Moreover, despite positive contribution to some potential ES, studies in China (Brancalion and Chazdon 2017) and Ethiopia (Lemessa et al. 2022; Tesfaw et al. 2022) have indicated that monoculture plantations, such as eucalyptus, had led to losses of bird and bee diversity.

Finally, changes in potential ES were not uniform across the landscape. For instance, increases in erosion control and carbon storage were most pronounced for kebeles currently dominated by arable land and pasture, and changed to cash crops under this scenario. These kebeles were also more negatively affected by loss of crop production and livestock feed (Figs. 2, 3). Crop production showed trade-off with coffee production, carbon storage, erosion control and woody-plant richness because these potential ES increased along with increase in cash crops while crop production and livestock feed decreased (Fig. 3).

4.1.3 'Coffee and conservation'

Changes in potential ES provision under this scenario were similar to the 'Gain over grain' scenario (Table 4, Figs. 2, 3). Increases in potential ES such as woody-plant richness, erosion control, and carbon storage were the results of maintained existing vegetation cover, restoration of the degraded steep farmland, and diversification of cropping systems using fruits and vegetables (Jiren et al. 2020). Despite these positive impacts, substantial decreases in potential crop production and

livestock feed by about 46% and 22%, respectively (Table 4), could negatively affect the local well-being in the short term.

The potential decreases in crops and livestock could be substituted to an extent by a substantial increase in fruits and vegetable in the landscape (Table 4). Moreover, a review by Tamburini et al. (2020) showed that agricultural diversification promoted biodiversity and the delivery of multiple ES without compromising crop yield. Further, local community in this scenario would generate income from the development of eco-tourism. Additionally, the climatically driven shift in shade coffee to high altitudes (Moat et al. 2017) could increase shade coffee production in this scenario, and thereby also benefit the local community. Last, this scenario would also help in avoiding or minimizing deforestation, because deforestation is typically lower in forest used for coffee production than in forest without coffee (Hylander et al. 2013; Takahashi and Todo 2013).

Disaggregated results at the kebele level are very similar to the 'Gain over grain' scenario – in which increases in woody-plant richness, erosion control, and carbon storage were high for many kebeles, especially those currently dominated by arable land (Fig. 2). Similar trade-offs and synergies between pairs of potential ES with 'Gain over grain' scenario was observed (Fig. 3), but it is due restoration of degraded farmland that decreased potential crop production and livestock feed. As such, maintaining the current woody vegetation and restoring the degraded farmland areas could potentially preserve the current multifunctionality of the landscape, thereby serving both ecosystems and human-wellbeing.

4.1.4 'Mining green gold'

Under this scenario, coffee production increased by more than two times. This increase could have the potential benefit to increase export and thus generate foreign income at the national level (Rahmato 2014; Jiren et al. 2020). However, other potential ES – woody-plant richness, carbon storage, erosion control, crop production and livestock feed – all decreased (Table 4). As such, this scenario revealed the impact of intensification via monocultures – ES provision was limited to few services, and the benefits would likely accrue to limited groups of individuals or companies (e.g., Rahmato 2014; Moreda 2017; Rasmussen et al. 2018). Furthermore, the current available evidence on coffee plantations in the study area indicated that coffee investment companies did not allow the local community to access forest based ES from their investment area (Tadesse et al. 2014b; Ango 2018). Such restriction could also affect the livelihoods of the local community who closely depend on forest products such as fuelwood (Ango 2018; Schultner et al. 2021; Shumi et al. 2021).

Evidence from Latin America also indicated that, even though modern coffee plantation increases coffee yield, it increased forest loss, soil erosion, biodiversity loss, and chemical runoff, thus threatening the long-term sustainability of ecosystems (Staver et al. 2001; Rappole et al. 2003). Such negative environmental impacts have far reaching consequences beyond the landscape, for instance in agricultural production of downstream areas (Buytaert et al. 2011; Ighodaro et al. 2013).

Notwithstanding the overall trade-off between coffee and other ES in this scenario, the projected changes were not uniform across the landscape (Fig. 2). Especially kebeles with a high level of woody-plant richness, erosion control, carbon storage, crop production and livestock feed in the current landscape would stand to lose much of this potential under this scenario. This is also reflected in correlation analysis (Fig. 3) in which coffee production almost showed no correlation with carbon storage, erosion control, and woody-plant richness because increase in coffee production in farmland increased these potential ES, while increase in coffee production in forest decreased these potential ES. Even though the previous findings by Hylander et al. (2013) and Takahashi and Todo (2013) concluded that coffee presence slows down deforestation, which by implication minimizes soil loss and maintains carbon storage, disaggregated results of the landscape at the kebele level showed the effect of coffee presence on erosion control and carbon storage differed across the kebeles. Intensive coffee plantations (unlike forest-grown coffee) led to increased soil loss and decreased carbon storage in kebeles currently dominated by forest. The

possible national benefits of large-scale expansion of coffee plantations therefore need to be considered carefully, especially in the context of a biodiversity hotspot where local people have strong ties with local ecosystems.

4.1.5 'Food first'

Under this scenario, crop production increased by more than two times (Table 4) by large-scale agricultural expansion and intensification. This scenario has the potential to boost national food production levels (Jiren et al. 2020), but might come at the expense of the local community's access to food and ES (e.g., Rahmato 2014; Moreda 2017; Rasmussen et al. 2018). Similar tradeoffs between crop production and other ES have been observed for large-scale agricultural intensification across the world (e.g., Rasmussen et al. 2018; Beckmann et al. 2019; Kim et al. 2022). Similar to the 'Mining green gold' scenario discussed above, this scenario could have negative long-term impacts on both society and the environment.

Disaggregation of results to the kebele level under this scenario indicated that cereal crop production increased and other ES decreased in almost all kebeles (Fig. 2). Those few kebeles where crop production did not change were characterized by complex topography that was not suitable for industrialized farming.

5. Conclusion

Potential ES changes differed across the scenarios in line with LULC changes. However, the changes were not uniform across the landscape. Disaggregated analysis at kebele level showed the changes were differed across the kebeles for all scenarios. Our findings provide valuable signals for regional decision-makers and other stakeholders, because they illustrate the plausible effects of land-use scenarios on potential ES in the area at landscape scale and kebele level, with important implications for the future of local community well-being. Our results indicated that scenarios of large-scale agricultural intensification are more likely to only address narrowly defined goals, such as the increase in provisioning services, but would imply major trade-offs regarding regulating, cultural and supporting ES. Such tradeoffs may cause unwanted consequences both locally and beyond; hence, detailed information on plausible outcomes of different land-use scenarios is important. Here, our potential ES maps of land-use scenarios provide useful information for the landscape in southwestern Ethiopia that could support decision-makers and stakeholders for planning for the future of the landscape. Based on our finding, the 'Coffee and conservation' scenario would be most effective to conserve ecosystems and provide human well-being.

Declaration of interest statement

All authors declare no conflict of interest.

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Data availability

The data that support the findings of this study are available from the corresponding author, [DWD], upon reasonable request.

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Supplementary material

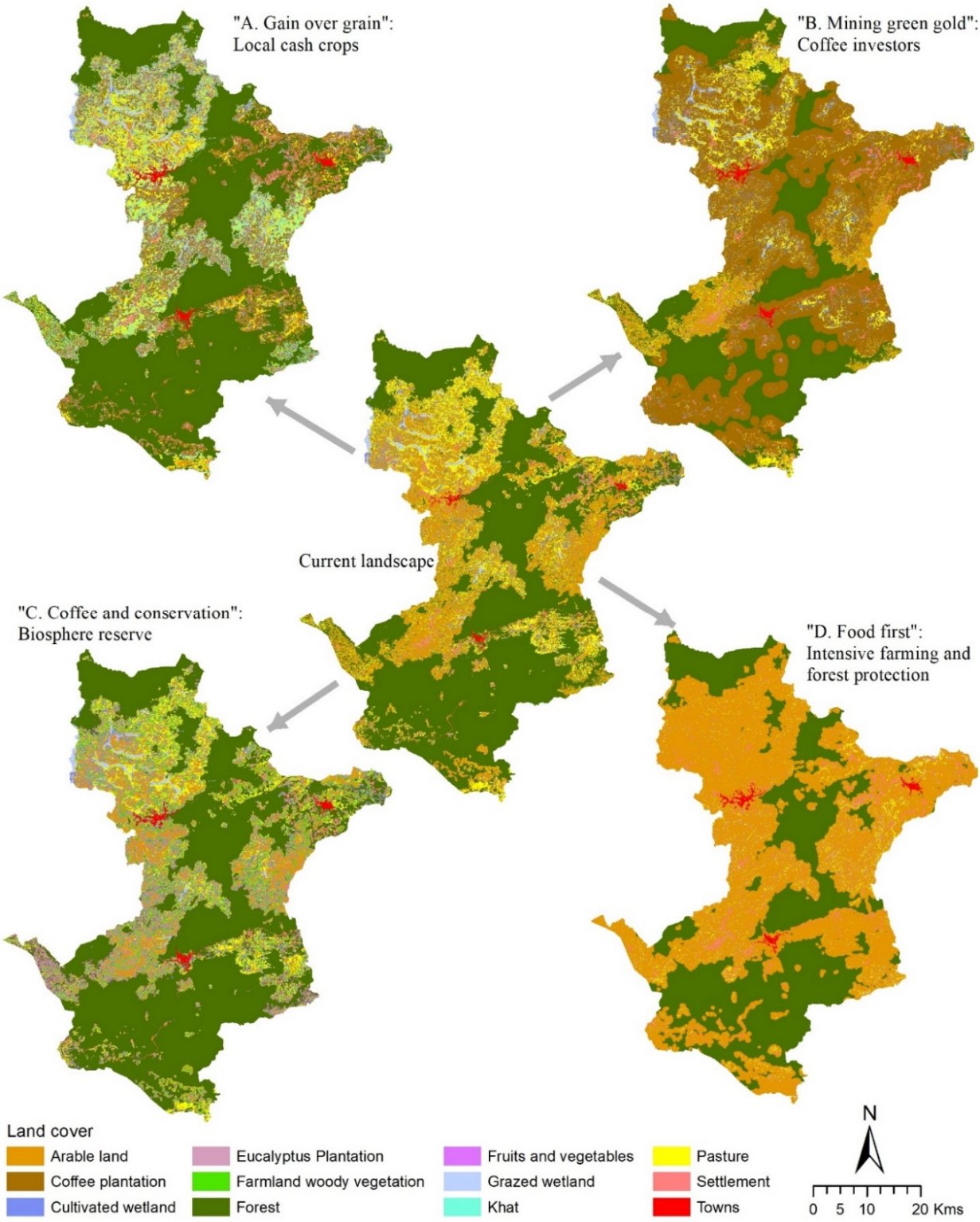

Figure S1. LULC map of the current landscape and land-use scenarios (reproduced from Duguma et al. 2022).

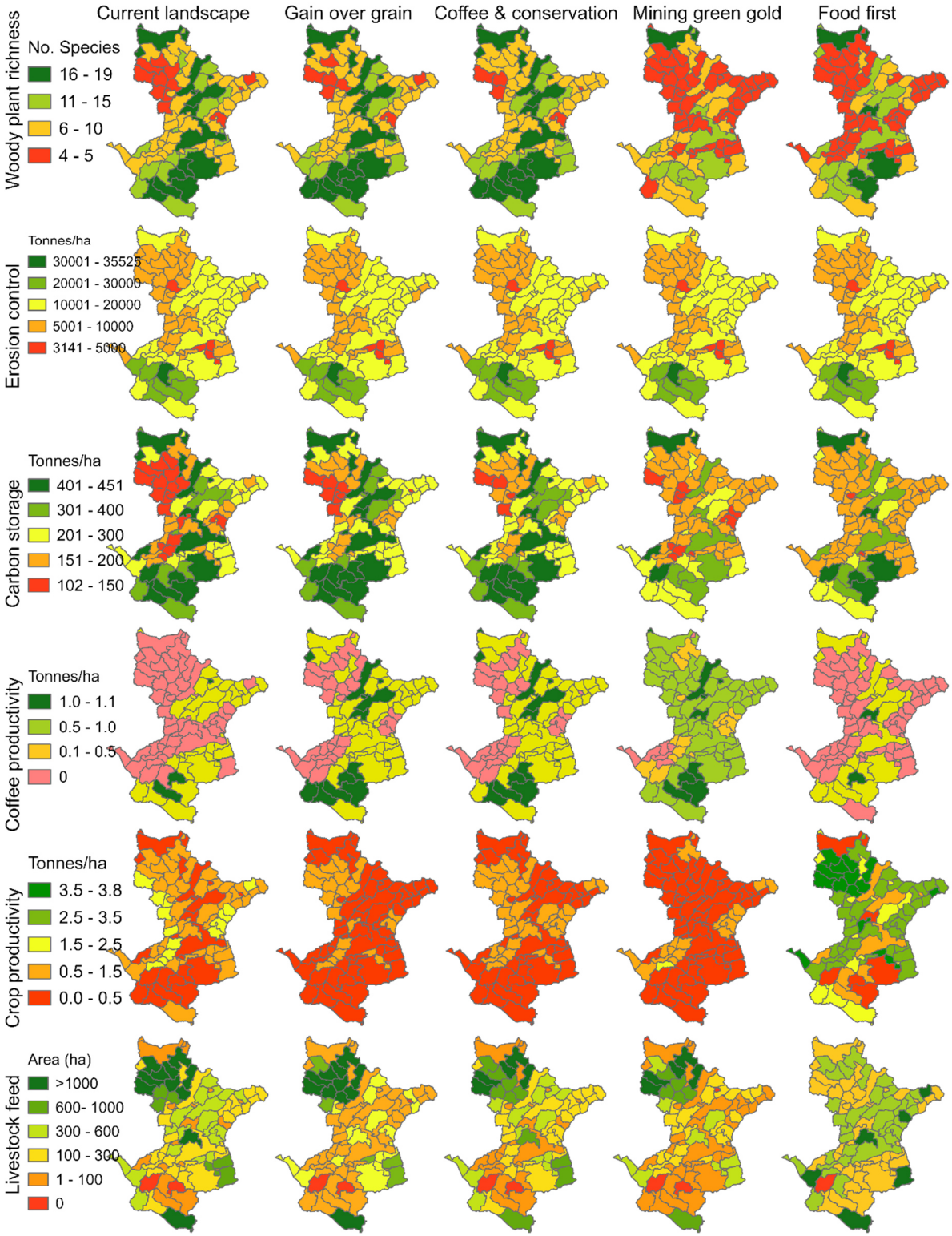

Figure S2. Absolute values of potential ES for the current landscape and land-use scenarios. Class boundaries were defined using manual classification for visualization purposes and for comparison across the scenarios for individual potential ES.

Table S1. Potential ES, indicators, and units.

Category	ES	Indicator	Units
Regulating	Carbon storage	Total carbon	tonnes
	Erosion control	Avoided erosion	tonnes
Supporting	Biodiversity	Woody-plant richness	count
Provisioning	Crop production	Weighted average for maize, teff, and sorghum production	tonnes
	Coffee production	Coffee production	tonnes
	Cattle feed	Area of pasture land	hectares

Table S2. Input variables to map erosion control.

Data	Source
Digital Elevation Model (DEM)	AsterDEM 30 m resolution (NASA/METI/AIST/Japan Spacesystems and U.S./Japan ASTER Science Team 2009).
Rainfall Erosivity Index (R)	Panagos et al. (2017)
Soil Erodibility (K)	Hurni et al. (2015), (Hengl et al. 2017)
Land Use/Land Cover	Duguma et al. (2022)
P and C coefficients	Hurni et al. (2015)
Biophysical table	Compiled by authors based on Duguma et al. (2022) and Hurni et al. (2015)

Table S3. Parameters and their values used for the model: Threshold flow accumulation (number of pixels) - the number of upslope pixels that must flow into a pixel before it is classified as a stream; ICO and Kb are calibration parameters that define the shape of the Sediment Delivery Ratio conductivity index; and Max SDR (maximum theoretical Sediment Delivery Ratio) average value. For ICO, Kb, and Max SDR default values were used. We conducted the model with different flow accumulation threshold (including the default flow accumulation threshold = 1000 cells, and additional user adjusted flow accumulation threshold at 3000 and 5000 cells). We compared the result of the subsequent models with the available secondary data of stream networks in the study region, and used the model output with the flow accumulation threshold of 5000 cells, which matches more with the available data of stream networks.

Parameters	Values
Threshold Flow Accumulation (TFA)	5000
Borselli k parameter kb	2
Borselli ICO papameter	0.5
Max SDR value	0.8

Table S4. Biophysical variables for LULCs compiled from literature based on LULC classes (Duguma et al 2022) and c and p coefficients (Hurni et al 2015). usle_c (ratio) stands for cover-management factor for the USLE model. Smaller values (closer to 0) indicate that less erosion is likely to come from the respective LULC type. Values closer to 1 indicate that more erosion is likely to come from the respective LULC type. usle_p (ratio) stands for support practice factor for the USLE. A value of 1 indicate that no erosion-reduction practices are being done (or, information on practices is lacking) - in this case P will have no effect on the USLE result.

LULC classes	**usle_c**	**usle_p**
Arable land	0.5	1
Coffee plantation	0.05	1
Cultivated wetland	0.1	1
Eucalyptus plantation	0.05	1
Farmland woody vegetation	0.01	1
Forest	0.01	1
Fruits and vegetables	0.05	1
Grazed wetland	0.04	1
Khat	0.05	1
Pasture	0.05	1
Rural settlement	0.4	1
Towns	0.4	1

Table S5. Productivity for crops and coffee used to calculate production. The table shows crop productivity for current landscape, 'Gain over grain', 'Coffee and conservation' and 'Mining green gold scenarios'. For 'Food first' scenario, the baseline for crop productivity used was for Teff (2.2), Maize (6.5), and Sorghum (3.3) based on the recent research result from farm yield (Belachew et al. 2022) that is equivalent to agricultural intensification. Similarly for coffee, the table shows the productivity for current landscape, 'Gain over grain', 'Coffee and conservation', and 'Food first' scenarios. For 'Mining green gold' scenario, the baseline for coffee productivity used was 1.13 based on the recent research result on coffee plantation in the study area (Zewdie et al. 2022).

Crops / Coffee	**Productivity (tonnes/ha)**	**Assigned weights**	**Reference**
Teff	1.8	0.42	Central Statistical Agency (CSA) (2018)
Maize	4.1	0.29	Central Statistical Agency (CSA) (2018)
Sorghum	2.9	0.15	Central Statistical Agency (CSA) (2018)
Coffee	0.65		Central Statistical Agency (CSA) (2018)

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Appendix II: A shared vision for the landscapes of southwestern Ethiopia

Tolera S. Jiren, David J. Abson, Maria Brueck, Joern Fischer, Jan Hanspach

Pensoft Publishers, Sofia (2023)

URL: https://books.pensoft.net/books/13390[2]

[2] Due to the extensive length of this policy booklet, it is not included here, but it can be accessed online via the weblink.

Overview of articles included in the doctoral thesis

(in accordance with the Guideline for cumulative dissertations enacted at the Faculty of Sustainability in January 2012)

Article No.	Bibliography	Publication Status	Specific author contributions	Specific contribution of PhD candidate	Weighing Factor	Presentation at conference
II	Brück, M., D. J. Abson, J. Fischer, and J. Schultner. 2022. Broadening the scope of ecosystem services research: Disaggregation as a powerful concept for sustainable natural resource management. Ecosystem Services 53:101399. doi: 10.1016/j.ecoser.2021.101399.	Published in Ecosystem services (IF = 7.6)	**Maria Brück**: conceptualization, writing (original draft), review & editing; **David J. Abson, Joern Fischer, Jannik Schultner**: conceptualization, review & editing	Co-author with predominant contribution	1.0	
III	Brück, M., J. Fischer, E. Law, J. Schultner, and D. Abson. 2023. Drivers of ecosystem service specialization in a smallholder agricultural landscape of the Global South: a case study in Ethiopia. Ecology and Society 28(3). doi: 10.5751/ES-14185-280301.	Published in Ecology & Society (IF = 5.275)	**Maria Brück**: conceptualization, data analysis and interpretation, writing (original draft), review & editing; **Joern Fischer**: data interpretation, review & editing; **Elizabeth Law**: data analysis and interpretation, review & editing; **Jannik Schultner**: review & editing; **David J. Abson**: conceptualization, data interpretation, review & editing	Co-author with predominant contribution	1.0	Brück, M., Abson, D.J., Duguma, D.W., Fischer, J., Schultner, J., 2021. Ecosystem service flows from southwestern Ethiopia: telecoupling, comparative advantage and specialization. ESP Europe 2021 Conference, Tartu, Estonia, June 2021.
IV	Brück, M., J. Schultner, B. B. Negash, F. D. Damu, and D. J. Abson. Plural valuation in southwestern Ethiopia: Disaggregated ecosystem service values in a smallholder landscape: *Major revisions with People and Nature.*	Major revisions in People and Nature (IF = 6.1)	**Maria Brück**: conceptualization, data analysis and interpretation, writing (original draft), review & editing; **Jannik Schultner**: review & editing; **Birhanu Bekele Negash**: data collection, review & editing; **Dadi Feyisa Damu**: data collection, review & editing; **David J. Abson**: conceptualization, data interpretation, review & editing	Co-author with predominant contribution	1.0	Brück, M., Abson, D.J., 2022. Assessing equity implications in the context of ecosystem services: disaggregation as a means for more equitable policy making. 14th Conference of the European Society for Ecological Economics, Pisa, Italy, June 2022.
V	Brück, M., F. Benra, D. W. Duguma, J. Fischer, T. S. Jiren, E. Law, M. Pacheco-Romero, J. Schultner, and D. J. Abson. A social-ecological approach to equitable land use decision making: *Under Review in Ambio.*	Under review in Ambio (IF = 6.5)	**Maria Brück**: conceptualization, data analysis and interpretation, writing (original draft), review & editing; **Felipe Benra, Dula Wakassa Duguma, Joern Fischer, Tolera Senbeto Jiren, Elizabeth Law, Manuel Pacheco-Romero, Jannik Schultner**: conceptualization, review & editing; **David J. Abson**: conceptualization, data interpretation, review & editing	Co-author with predominant contribution	1.0	
App. I	Duguma, D. W., M. Brück, G. Shumi, E. Law, F. Benra, J. Schultner, S. Nemomissa, D. J. Abson, and J. Fischer. Future ecosystem service provision under land-use change scenarios in southwestern Ethiopia: *Under Review in Ecosystems and People.*	Under review in Ecosystems and People (IF = 5.1)	**Dula Wakassa Duguma:** conceptualization, data analysis and interpretation, writing (original draft), review & editing; **Maria Brück, Girma Shumi, Elizabeth Law, Felipe Benra, Jannik Schultner, Sileshi Nemomissa, David J. Abson, Joern Fischer:** conceptualization, review & editing	Co-author with small contribution	0	

Appendix

Declaration (according to § 16 of the guideline for cumulative dissertations):

I avouch that all information given in this appendix is true in each instance and overall.

Hamburg, 31st of August 2023

Maria Brück

Explanatory Notes:

Specific contribution of PhD candidate submitting the doctoral thesis / Author status according to § 12 of the guideline for cumulative dissertations

- Single author = own contribution amounts to 100%.
- Co-author with predominant contribution = own contribution is greater than the individual share of all other co-authors and is at least 35%.
- Co-author with equal contribution = (1) own contribution is as high as the share of other co-authors, (2) no other co-author has a contribution higher than the own contribution, and (3) the own contribution is at least 25%.
- Co-author with important contribution = own contribution is at least 25%, but is insufficient to qualify as single authorship, predominant or equal contribution.
- Co-author with small contribution = own contribution is less than 20%.

Weighing Factor according to § 14 of the guideline for cumulative dissertations

- Single author 1.0
- Co-author with predominant contribution 1.0
- Co-author with equal contribution 1.0
- Co-author with important contribution 0.5
- Co-author with small contribution 0

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Declaration

I hereby declare that I have not yet taken any doctoral examination or applied for admission to such.

I further certify that the dissertation with the title "Disaggregated analysis of ecosystem services in southwestern Ethiopia" has not been submitted to any representative of any faculty, that I have submitted the dissertation only in this and no other doctoral examination, and that this doctoral examination has not been preceded by any finally failed doctoral examinations.

I furthermore declare that I have written the submitted dissertation "Disaggregated analysis of ecosystem services in southwestern Ethiopia" independently and without unauthorized aids. I have not made use of other aids and writings than those indicated. All passages taken in verbatim or substance from other works have been identified.

Hamburg, 31st of August 2023

Maria Brück