Biodiversity and ecosystem services under different future land-use scenarios in southwestern Ethiopia

LEUPHANA
UNIVERSITÄT LÜNEBURG

Doctoral thesis by Dula Wakassa Duguma

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Biodiversity and ecosystem services under different future land-use change scenarios in southwestern Ethiopia

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Submitted by
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Dedication

To my beloved father Wakassa Duguma whom I lost on 19 May 2019;
and to my beloved family Abebaye Tesgera, Milkessa Dula and Heeran Dula.

Acknowledgements

My PhD was not an easy journey. I was through a very difficult and challenging times in the middle of my PhD period, taking care of kids, sleep deprivation, taking care of my wife who has faced health issues, it is a lot! Thank you GOD for helping me through this difficult time and giving me the strength to keep going. Doing PhD in such circumstances is not easy. However, the support I got from extraordinary people helped me to achieve my target and pass through these difficulties.

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Preface

This cumulative dissertation is submitted for the degree of Dr. rer. nat. at Leuphana Universität Lüneburg, Germany. It consists of five chapters based on empirical research conducted in southwestern Ethiopia between 2020 and 2023. The research described herein was part of an interdisciplinary research project *"Towards a Sustainable Bioeconomy: A Scenario Analysis for Jimma Coffee Landscape in Ethiopia – funded by German Ministry for Education and Research (BMBF), Project Number 63300083".* The empirical studies presented in this dissertation contribute to better understand the future of landscape change and its impact on biodiversity and ecosystem services by integrating scenario planning with future land-use mapping. Two chapters (II and III) are published and the other two chapters (IV and V) are in revision in international scientific journals. I, the author of this dissertation, conducted all research presented in this dissertation and am the lead author of all manuscripts. A reference to the journal in which a chapter is published or in revision as well as its status and contributing co-authors are presented at the title page of each chapter. A list of references is provided at the end of each chapter, and some chapters are followed by supporting information. In Chapter I, I alternate between the pronouns "I" and "we", to acknowledge the collaborative nature of the research. Due to the stand-alone nature of the chapters, stylistic differences (such as British or American English, formatting of references and structure of the papers) and some repetitions in the text of this dissertation was unavoidable.

It is my hope that this research will support stakeholders and decision-makers to avoid the undesirable consequences of different development trajectories and choose scenarios of the future that could conserve biodiversity and support human well-being.

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Abstract

Tropical ecosystems are critical for biodiversity conservation and local people's livelihood sustenance. However, these ecosystems are under high pressure from land-use and land cover (LULC) change, which is further projected to intensify and increase rapidly, thereby affecting biodiversity and the provisioning of vital ecosystem services (ES). It is thus important to understand how LULC might change in the future and how such changes could affect biodiversity and ES provisioning in a given landscape of tropical ecosystems. Scenario planning has become an increasingly popular tool and technique to produce narrative scenarios of the future landscape change. Thus, quantifying changes under different land-use scenarios could be a means to elucidate the synergies and trade-offs within the scenarios. In this dissertation, I examine the future of biodiversity and ES provisioning for different plausible land-use scenarios in southwestern Ethiopia.

First, I translated four future plausible narrative social-ecological land-use scenarios (namely, 'Gain over grain', 'Coffee and conservation', 'Mining green gold' and 'Food first') developed for southwestern Ethiopia by participatory scenario planning into spatially explicit LULC scenario maps. Results showed distinct LULC changes under each scenario. For instance, forest cover under the 'Gain over grain' and 'Coffee and conservation' scenarios remained similar to the current landscape covering about half of the landscape, in contrast it decreased by 27% and by about 18% under 'Mining green gold' and 'Food first' scenarios, respectively. Coffee plantation and arable land for cereal crop production covered about half of the landscape under 'Mining green gold' and 'Food first' scenarios, respectively. Second, I investigated the impact of these land-use scenarios on biodiversity by specifically modelling woody plant species richness in farmland and forest. Both indicators of human disturbance and environmental conditions were used. The results indicated that the 'Mining green gold' and 'Food first' scenarios would result in strong losses of biodiversity, whereas the 'Gain over grain' scenario largely maintained biodiversity relative to the baseline. Only the 'Coffee and conservation' scenario showed positive changes for biodiversity that are likely viable in the long run. Third, I also investigated the effect of these land-use scenarios on woody plant-based ES provisioning by combining woody plant species with household surveys on how woody plants were used by the local community. I modelled and predicted the current and future availability of woody plant-based ES under the four scenarios of landscape change. The

results showed that land-use scenarios with intensified food or cash crop cultivation would lead to the contraction of woody-plant based ES from farmland to forest patches, implying increased pressure on remaining forest patches. In such a context, attempts to ‘spare’ forest patches from local people will likely be ineffective or alternatively, will have serious negative consequences for local livelihoods. I further modelled and mapped the spatial distribution of six ES: two regulating services (erosion control and carbon storage), three provisioning services (coffee production, crop production and livestock feed) and a supporting service (woody plant richness) for the current landscape and the four land-use scenarios. Results showed 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 in the long run.

This study provides methodological and empirical contributions to the developing fields of scenario planning, social-ecological systems analysis, conservation and landscape change sciences. In addition, it has practical implications for local stakeholders and decision-makers, who can draw on findings for a better-informed land-use management.

Overall, the findings of this dissertation showed the importance of integrating future land-use mapping with participatory, narrative-based scenarios to assess the social-ecological outcomes of alternative futures. The spatially explicit maps of LULC change, biodiversity and ES (at different scales) could be used as a valuable input to support stakeholders and decision-makers to weigh the advantages and disadvantages of different development trajectories on ecosystems and human well-being and to avoid or minimize future undesirable consequences. To this end, apart from the benefits of coffee production under ‘Mining green gold’ and crop production under ‘Food first’ scenarios, the findings under these scenarios of large-scale agricultural intensification point to a potentially high loss of biodiversity and ES. These two scenarios could have a negative long-term impact on ecosystems and human well-being. Finally, the ‘Coffee and conservation’ scenario, which involves the creation of a new biosphere reserve, appears to be the most sustainable scenario. This scenario could result in a sustainably managed, diversified landscape which could make major contributions to biodiversity conservation and human well-being in the region and beyond.

Chapter I

Chapter I

Biodiversity and ecosystem services under different future land-use scenarios in southwestern Ethiopia

Introduction

Tropical ecosystems are hyperdiverse (Barlow et al. 2018) and critical for global biodiversity conservation and local livelihood sustenance (Kehoe et al. 2017; Barlow et al. 2018). However, these ecosystems are under high pressure from LULC change, which is further projected to intensify and increase rapidly affecting biodiversity and ecosystem service (ES) provisioning (Sala et al. 2000; Powers and Jetz 2019; Schirpke et al. 2020). It is thus important to understand how LULC might change in the future and how it would affect biodiversity and ES provisioning in a given landscape of tropical ecosystems. In this dissertation, I examine the biodiversity and ES provisioning outcomes based on different plausible future land-use scenarios in southwestern Ethiopia. This region of Ethiopia is a mosaic landscape of forests and farmlands in a biodiversity hotspot area supporting high biodiversity and local livelihoods. In this section, I briefly review land-use change and its impact on biodiversity and ES, followed by scenario planning as a tool to understand the future of LULC change. I also introduce the narrative social-ecological land-use scenarios for southwestern Ethiopia developed by participatory scenario planning. Overall, this section provides a brief background to the research goal and discussion of the findings.

Land-use change

Land-use change reveals the past, present and future of people (Houghton 1994; Foley et al. 2005) because people depend on land for food, energy, living space and development (e.g., Foley et al. 2005; Song et al. 2018). Since the Industrial revolution, human activity has become the main driver of global environmental change (Rockström et al. 2009; Kim et al. 2018; Díaz et al. 2019) affecting the resilience of the ecosystems (Steffen et al. 2015). Land-use activities such as the conversion of forests to agriculture or into urban areas, changing management practices on human-dominated lands, intensifying farmland production and the introduction of new species (Houghton 1994; Foley et al. 2005; Rockström et al. 2009) adversely affect ecosystems and threaten human well-being (WWF 2020).

As income and populations continue to grow, the demand for food, natural resources and the pressure on ecosystems also increases (Foley et al. 2005; Song et al. 2018). Such unparalleled appropriation of ecosystems, mainly caused by modern agriculture (Foley et al. 2005; Rockström et al. 2009), cause a “serious risk for the quality of life of people” (Díaz et al. 2019), and protection of human well-being is basically linked to conservation of the natural ecosystems (Steffen et al. 2015; WWF 2020).

Recent advances in satellite observations contribute substantially to our current understanding of the natural ecosystems such as the global extent and change of LULC (e.g., Geist and Lambin 2002; Song et al. 2018; Winkler et al. 2021). These global-scale studies of LULC change found a decrease in forest cover and an expansion of agricultural land. For instance, Hansen et al. (2013) showed that globally, about 2.3 million km^2 of forest were lost due to deforestation from 2000 to 2012, out of which the tropics experienced the greatest forest loss (about 2101 km^2/year). Similarly, between 1960 and 2019, Winkler et al. (2021) identified a global net loss of forest area of about 0.8 million km^2 and an expansion in cropland and pasture by about 1.0 and 0.9 million km^2, respectively. Furthermore, a recent report by FAO’s remote sensing survey indicated that the annual rate of net forest loss mainly due to conversion to cropland has increased in Africa from 3.3 million hectares between 1990 and 2000 to 3.9 million hectares between 2010 and 2020 (FAO 2020).

Even though there are other immediate human actions (such as infrastructure development) and underlying factors (such as economic, institutional, technological, cultural and population growth) which cause tropical deforestation (e.g., Houghton 1994; Geist and Lambin 2002), several studies (e.g., Kehoe et al. 2017; Song et al. 2018; FAO 2020; Pendrill et al. 2022) indicate that agricultural expansion is by far the main driver of tropical deforestation. It is further projected that tropical ecosystems will even face greater pressures in the future from LULC change that is projected to further intensify and increase rapidly (Song et al. 2018; Powers and Jetz 2019) due to the projected increase in population, per-capita food consumption and trade (Laurance et al. 2014; Song et al. 2018; WWF 2020). Such projected future LULC changes will significantly affect biodiversity and ES provisioning (Sala et al. 2000; Powers and Jetz 2019; Schirpke et al. 2020).

Impact of land-use change on biodiversity and ecosystem services

Of the main direct threats to terrestrial biodiversity, i.e., land-use change, climate change, overexploitation, pollution and invasive species (Sala et al. 2000; Maxwell et al. 2016; Caro et al.

2022; Jaureguiberry et al. 2022), LULC change is currently the most important direct driver of biodiversity loss on land (WWF 2020; Caro et al. 2022; Jaureguiberry et al. 2022). The impact of LULC change (mainly in the form of rapid agricultural expansion, intensification of farming and deforestation) could even exceed that of climate change by three to ten times (Caro et al. 2022) and it is much stronger in tropical regions, especially in Africa (WWF 2020; Jaureguiberry et al. 2022).

LULC change causes biodiversity loss by changing the composition, distribution, abundance and functioning of biological diversity and related processes (Foley et al. 2005; Millennium Ecosystem Assessment 2005; Díaz et al. 2019). The latest Living Planet Index report shows that, globally, on average, vertebrate populations have declined by 68% (the largest declines are in Latin America [94%], Africa [65%] and Southeast Asia [45%]) and plant diversity have declined by 22% (WWF 2020). The impact of LULC change on biodiversity depends on the intensity of change, the configuration of land-use patterns and the spatial distribution of natural biophysical variables (Zebisch et al. 2004; Foley et al. 2005). These impacts are very high in "hyperdiverse tropical ecosystems" (Barlow et al. 2018), which are critical to global biodiversity conservation (Barlow et al. 2018; WWF 2020) but were characterized by relatively low conservation activity and high agricultural growth (Kehoe et al. 2017). This quality of tropical ecosystems, i.e., being a high biodiversity area and also one suitable for agricultural production (Kobayashi et al. 2019; Caro et al. 2022), will create further loss of biodiversity due to the exploitation of these ecosystems (Caro et al. 2022).

LULC change and the resulting loss of biodiversity alter the generation and provisioning of ES – i.e., the benefits that people obtain from the ecosystems (Millennium Ecosystem Assessment 2005). This continued loss of biodiversity will negatively affect human well-being, especially in the tropics, where natural ecosystems play key role in daily livelihoods of people (WWF 2020). Tropical ecosystems are crucial for global biodiversity (Barlow et al. 2018; WWF 2020) and provide vital ES for both local and global communities, but have faced unprecedented pressures (Laurance et al. 2014; Suich et al. 2015; Shackleton et al. 2019). The integration of food production and biodiversity conservation has become a major challenge, particularly in the tropics (Laurance et al. 2014; Davis et al. 2020), where many landscapes are highly biodiverse (Kehoe et al. 2017;

Barlow et al. 2018) but where local people also strongly depend on local ecosystems to support their livelihoods (Estrada-Carmona et al. 2014; Suich et al. 2015; Shackleton et al. 2019).

To address this challenge, different land-use strategies such as the ‘land sparing’ vs. ‘land sharing’ model (e.g., Fischer et al. 2008; Phalan et al. 2011; Kremen 2015) have been widely applied. Land sparing involves a separated land-use approach in which some areas are strictly protected, while the remaining lands are used for intensive agricultural production (Green et al. 2005; Fischer et al. 2008; Phalan et al. 2011; Kremen 2015). In contrast, land sharing represents an integrated land-use approach involving agricultural production and conservation in which agricultural production is generated across larger areas under a biodiversity-friendly farming methods (Green et al. 2005; Fischer et al. 2008; Phalan et al. 2011; Kremen 2015). As both land-use strategies have been shown to have advantages and drawbacks (Fischer et al. 2008; Kremen 2015; Law et al. 2017), integrating these strategies could be useful in multifunctional agricultural landscapes of the tropics, an approach which may minimize biodiversity loss and maintain the continuous generation of ES (Seppelt et al. 2013; Grass et al. 2019). The projected increase in LULC change such as increase in crop demand for food, livestock feed and biofuels by agricultural expansion and intensification will aggravate pressure on biodiversity (Kehoe et al. 2017; Powers and Jetz 2019; Zabel et al. 2019) and affect cultural landscapes in ES provisioning (Foley et al. 2005; Hansen et al. 2013). Thus, in order to contribute to transformative change toward sustainability and better elucidate trade-offs, it is vital to evaluate what plausible future LULC changes might look like and how they would affect biodiversity and ES.

Scenario planning as a tool to understand the future impact of LULC change on biodiversity and ecosystem services

Scenario planning can be used to understand future landscape change and related social-ecological impacts. Scenario planning is a tool and technique to envision the future of landscape change (Alcamo et al. 2008) and to develop plausible and internally consistent descriptions of alternative scenarios (Peterson et al. 2003; IPBES 2016). Scenarios are neither predictions nor forecasts (Peterson et al. 2003; Alcamo et al. 2008); they can be defined as “a range of plausible future changes that may unfold grounded on a coherent and internally consistent set of assumptions about key driving forces, their relationships and their implications for biodiversity and ES" (Henrichs et al. 2010).

Modelling biodiversity and ES based on scenarios of LULC change can be useful for understanding plausible future biodiversity and ES loss (e.g., Sala et al. 2000; Leclère et al. 2020). However, most studies have modelled biodiversity and ES losses using climate scenarios developed at global and regional scale (e.g., GEO5 2012; IPCC 2013) at a coarse spatial resolution. Such large-scale scenarios are mostly expert driven, long-term and focus on international large-scale solutions to undesirable global change (Bürgi et al. 2022). These broad scale approaches are valuable, but they treat some of the landscape change drivers (e.g. spatial heterogeneity, topography, cultural factors, national policy) in highly simplified ways and cannot capture local realities (Nelson et al. 2009; Frame et al. 2018) at landscape scale, i.e., an area within fine-grained land cover mosaics ranging in extent from some square kilometers to hundreds of square kilometers (Fischer and Lindenmayer 2007). This limits the usefulness of large-scale scenarios for local stakeholders in local conservation planning and decision-making (Franklin 2010; Jaureguiberry et al. 2022). To assess plausible futures for a particular landscape, many scenario mapping exercises have downscaled regional or global scenarios to a more localised level (e.g., Verburg et al. 2006; Seppelt et al. 2013; Frame et al. 2018). While downscaling has the advantage of making local land-use scenarios more consistent and comparable across scales (Liu et al. 2015; Zhang et al. 2015; Schweizer and Kurniawan 2016), it often does not take local context properly into consideration (Alcamo et al. 2008; IPBES 2016).

On the contrary, scenarios developed at the landscape scale are mostly short-term and more stakeholder driven, and they aim to capture local realities (e.g., Malinga et al. 2013; Oteros-Rozas et al. 2015; Jiren et al. 2020). Such scenarios cover a large variety of views of the future including the potential influence of local policy planning (Peterson et al. 2003; Alcamo et al. 2008; Henrichs et al. 2010). These scenarios are mostly developed using participatory scenario planning, and the outcomes are qualitative narrative scenarios of the future (Alcamo 2008; Oteros-Rozas et al. 2015), mostly explained in storylines, images and diagrams (e.g., Hanspach et al. 2014; Booth et al. 2016; Jiren et al. 2020). Narrative scenarios have the advantage of being able to represent and integrate the views of several different stakeholders and experts and, thus, also complex cultural factors (e.g., Enfors et al. 2008; Mallampalli et al. 2016). As such, they can be used to raise awareness of local stakeholders and decision-makers about environmental problems and possible ways to solve them (Alcamo 2008; Henrichs et al. 2010). However, narrative scenarios do not provide quantitative information (Alcamo 2008; Booth et al. 2016; Bürgi et al. 2022), for instance quantitative information on LULC change. This information, however, is needed to understand and estimate the extent and type of LULC change in order to compute, model and analyze the implications of these changes on biodiversity or ES.

Quantitative scenarios provide numerical information in the form of tables, graphs or spatial maps, which are used to investigate future changes in the ecosystems due to changing driving forces (Alcamo 2008; Booth et al. 2016; Bürgi et al. 2022). These scenarios can also be used as a research tool to examine the relationship between specific policies and their consequences on ecosystems (Booth et al. 2016; Mallampalli et al. 2016; Bürgi et al. 2022). Although quantitative scenarios provide such useful information, they have also drawbacks in as much as information might not be accurate or complex processes in landscape change might be omitted (Alcamo 2008; Bürgi et al. 2022). Established standards of how to integrate information from qualitative studies into more quantitative driving forces of landscape change analysis are lacking (Bürgi et al. 2022).

Thus, connecting landscape-scale narrative scenarios to specific biodiversity and ES outcomes could be a means to identify potential synergies and trade-offs between alternative plausible futures. This can be approached by translating narrative scenarios into spatially explicit land-use scenario maps, and to model biodiversity and ES outcomes under each land-use scenarios. This approach can be particularly useful, because scenarios play out precisely depending on locally specific social-ecological conditions of the landscapes (Hanspach et al. 2014). Landscapes can be conceptualized as interlinked social-ecological systems (Wu 2013; Oteros-Rozas et al. 2015; Fischer et al. 2017) where the interaction of natural and human practices takes place (Plieninger et al. 2015; Bürgi et al. 2022). Analyzing the effects of future land-use change on biodiversity and ES in a social-ecological systems could contribute to improved decision-making related to ecological and human well-being, which are fundamental to sustainable development (Schirpke et al. 2020).

Social-ecological land-use scenarios of southwestern Ethiopia

Southwestern Ethiopia is a globally recognised biodiversity hotspot (Mittermmeier et al. 2011; Bellard et al. 2014), with large areas of Afromontane forests (Hylander et al. 2013). The study area is part of this biodiversity hotspot and consists of a forest-agricultural mosaic (Ango et al. 2014a; Dorresteijn et al. 2017) of three administrative districts in the Jimma zone of the Oromia region, namely Gera, Gumay and Setema, with a total area of about 2,800 km^2 (Fig. 1). Based on Ethiopia's multi-level governance system, districts are further subdivided into *kebeles* (Fig. 1). Kebeles are important social-ecological units where different local management, land-use planning and decision-making happen.

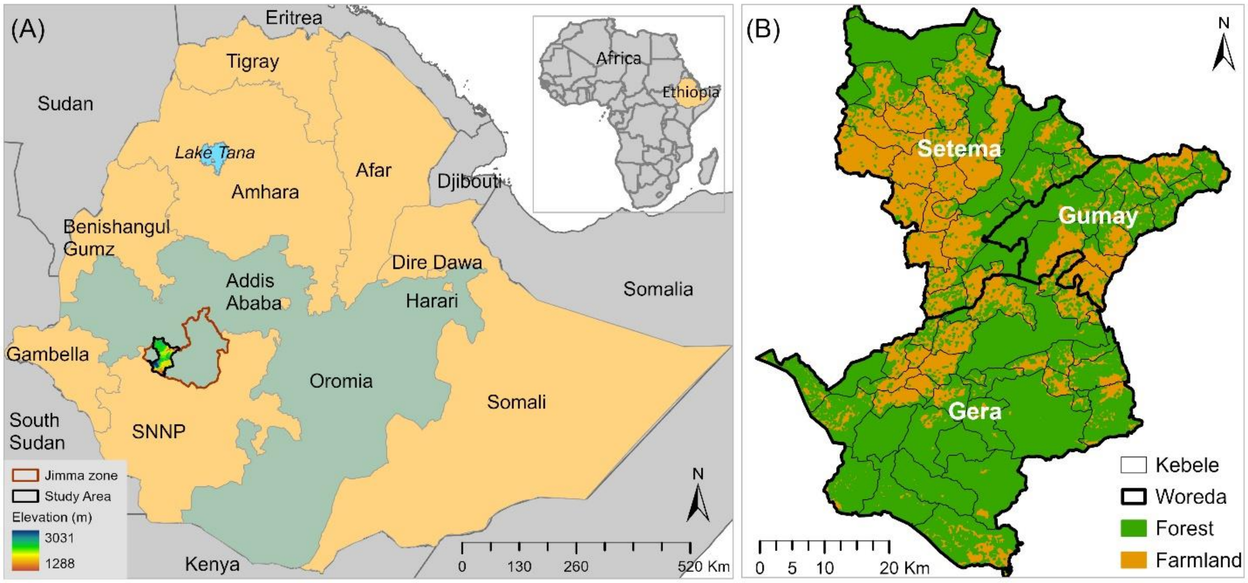


Fig.1. (A) the study area - delimited by black line with underlying elevation - in Jimma Zone, Oromia region (green grey) within Ethiopia (other regions are tan-colored). The small inserted map shows location of Ethiopia (tan-colored) in Africa; (B) the district boundaries (woredas; delimited by a thick 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.

The study area is the place where Arabica coffee (*Coffea arabica*) originates (Senbeta and Denich 2006). *Coffea arabica* is native to the region and naturally grows under the shade of trees in moist evergreen Afromontane forest. Topographically, the study area is undulating and falls within elevations of approximately 1,200 to 3,000 m above sea level (Fig. 1). It is a landscape which is dominated by smallholder farmers, whose main economic activities are dependent on subsistence farming of cereal crops, livestock rearing, coffee production and forest-based ES (Schultner et al. 2021; Shumi et al. 2021). The local population heavily depends on locally generated provisioning ES (Ango 2018; Schultner et al. 2021; Shumi et al. 2021) which are key to their livelihoods and well-being (Shumi et al. 2019a). There are evidences that smallholder farmers in the study area are shifting towards cash crops (Dharmendra Kumar et al. 2014; Gebrehiwot et al. 2016; Jaleta et al. 2016), and incidences of small-scale and medium-scale forest grabbing for coffee plantations have increased (Tadesse et al. 2014b; Ango 2018).

For this landscape, which is important from both social and ecological perspectives, four plausible qualitative social-ecological land-use scenarios (hereafter land-use scenarios) which envisioned the future until 2040 were developed in 2020 through participatory scenario planning (Jiren et al. 2020). The land-use scenarios were named ‘Gain over grain’, ‘Mining green gold’, ‘Coffee and conservation’ and ‘Food first’. About 35 stakeholders from different organizations and local community groups participated (for details see Jiren et al. 2020). Those 35 stakeholders, in turn, were based on an in-depth analysis of the stakeholder network in the study area (Jiren et al. 2018). The scenarios considered a wide range of plausible environmental, social and economic changes, and they are briefly summarized in Table 1.

Table 1. Brief summary of social-ecological scenarios envisioned for southwestern Ethiopia for the year 2040 (see Jiren et al. 2020 for details).

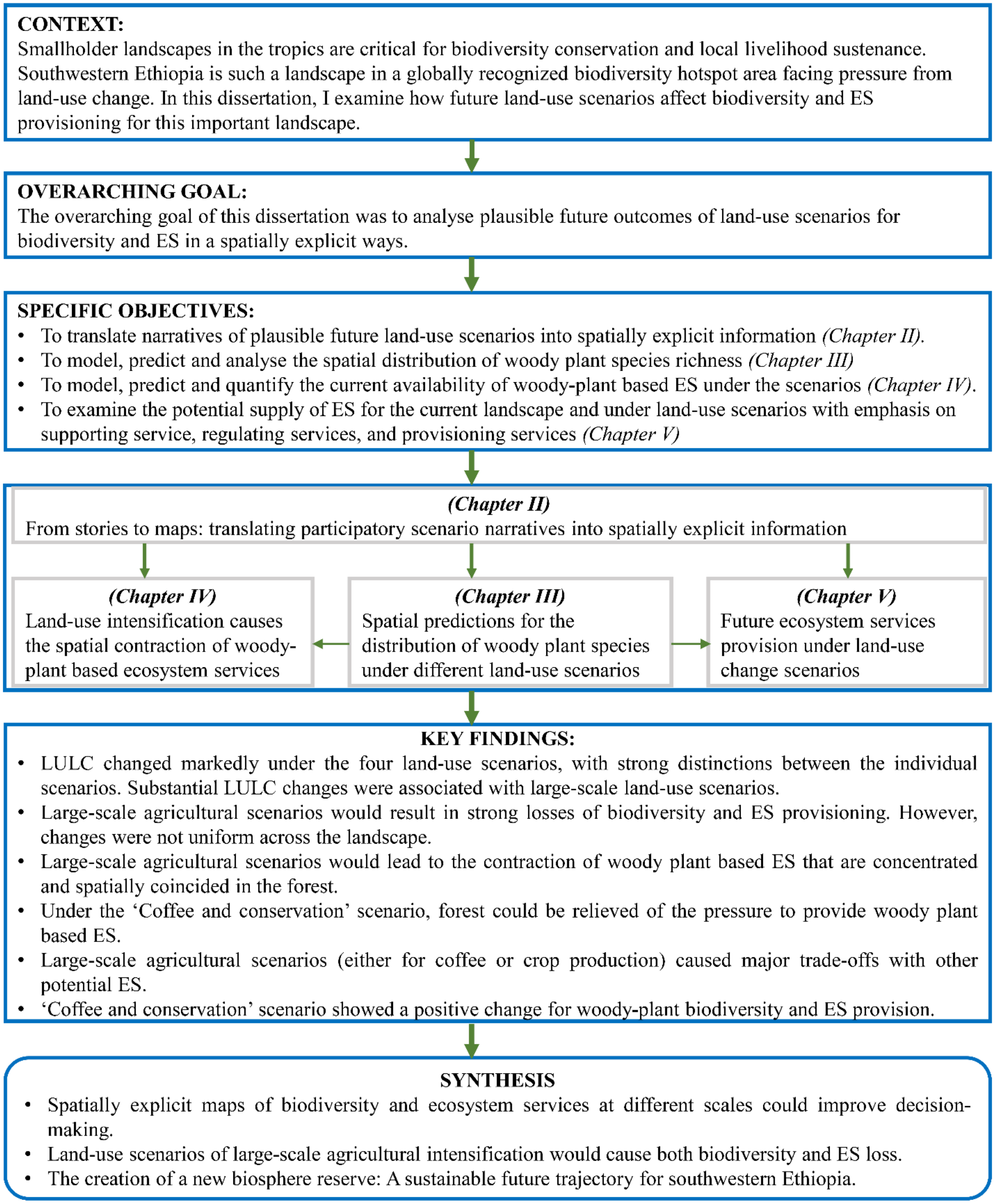
Scenario	**Description**
'Gain over grain': Local cash crops	This scenario prioritizes smallholder farmers' specialization and commercialization to boost development focused on cash crops such as coffee, the stimulant drug khat (*Catha edulis*) and fast-growing trees *(e.g. Eucalyptus)* on farmland. Farmers are encouraged to increase coffee production through newly created coffee plantations. Eucalyptus plantations primarily target degraded areas and marginal land. Khat plantations on former farmland are intensively managed. Traditional food cropping is abandoned in favor of these cash crops. 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.
'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. The landscape consists of intensively managed high-yielding coffee plantations, and relatively little food is produced. Smallholder land, communal land and forests conducive for coffee investment have been transferred to capital investors for the creation and expansion of coffee plantations. The use of non-native species for coffee shading is common. No integration between coffee production and biodiversity conservation. Local farmers are left to farm marginalized areas unsuitable for large-scale coffee plantations (e.g. steep hillslopes). Social injustice increases, and local and traditional knowledge is being lost.
'Coffee and conservation': Biosphere reserve	This scenario is based on a more balanced land-use approach and best-practice sustainable resource management, which combines sustainable agriculture, environmentally friendly coffee production and tourism driven by the failure of conventional agriculture and increasing global interest in sustainably grown coffee. The landscape is a diversified mosaic of forest and farmland consisting of a core zone with unused natural forest, a buffer zone for low-intensity production of local coffee, wild honey and other forest products and an outer zone with interspersed cropland, pastures, fruit and vegetables and tree plantations. Livestock production and communal grazing take place much like at present. Aggregate profits generated are modest, but social capital and cultural integrity are high.
'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 cereal food crops are now produced in region through intensive, large-scale agriculture, which involves extensive land consolidation, including the clearing of woody vegetation and the expansion of cropland into flatlands and drained wetlands. The landscape is dominated by cereal crop production. Intensified fruit and vegetable plots, as well as pastures for beef fattening and commercial beef production are also present, especially on steep slopes. Remaining patches of natural forest are strictly protected, and the local community is not permitted to access them. Social injustice increases and local and traditional knowledge are eroded.

Aims

My PhD dissertation was part of an interdisciplinary research project named "Towards a sustainable bio economy: a scenario analysis for the Jimma coffee landscape in Ethiopia," which aimed to identify environmental and socioeconomic outcomes of ES flows from increasingly teleconnected landscapes in the Global South. The overarching goal of this dissertation was to analyse plausible future outcomes of land-use scenarios for biodiversity and ES in a spatially explicit way with special emphasis on woody-plants and also to analyse the impacts of land-use scenarios on potential supply of ES such as erosion control, carbon storage, livestock feed, crop and coffee production in the study area. The overall structure of the dissertation is shown in Figure 2. Based on the results of land-use scenario maps, I modelled and assessed biodiversity and ES outcomes for the different land-use scenarios. The specific objectives that I addressed in my dissertation were:

1. To translate narratives of four plausible future land-use scenarios into spatially explicit land-use scenario maps.
2. To model, spatially predict and analyse the spatial distribution of woody plant species richness, both for the present-day situation and for the four land-use scenarios.
3. To model, predict and quantify the current availability of woody-plant based ES in the landscape and to analyze the potential changes thereof under the four land-use scenarios.
4. To map, analyze and interpret the potential supply of ES for the current landscape and under land-use scenarios with emphasis on supporting services (woody-plant richness), regulating services (erosion control and carbon storage) and provisioning services (coffee production, crop production and livestock feed); and to examine their synergies and trade-offs.

By doing so, this dissertation aimed to further advance our understanding of how different land-use scenarios can affect biodiversity and ES provisioning, and hence the resilience of the local social-ecological system, in general. Specifically, it contributes to the methodological development of how to integrate narrative scenario planning into future land-use mapping. It also represents an empirical contribution to future biodiversity and ES modelling and mapping. Further, this dissertation provides information that could support stakeholders and decision-makers in conservation planning and land-use management.



CONTEXT:
Smallholder landscapes in the tropics are critical for biodiversity conservation and local livelihood sustenance. Southwestern Ethiopia is such a landscape in a globally recognized biodiversity hotspot area facing pressure from land-use change. In this dissertation, I examine how future land-use scenarios affect biodiversity and ES provisioning for this important landscape.

OVERARCHING GOAL:
The overarching goal of this dissertation was to analyse plausible future outcomes of land-use scenarios for biodiversity and ES in a spatially explicit ways.

SPECIFIC OBJECTIVES:

- To translate narratives of plausible future land-use scenarios into spatially explicit information *(Chapter II)*.
- To model, predict and analyse the spatial distribution of woody plant species richness *(Chapter III)*
- To model, predict and quantify the current availability of woody-plant based ES under the scenarios *(Chapter IV)*.
- To examine the potential supply of ES for the current landscape and under land-use scenarios with emphasis on supporting service, regulating services, and provisioning services *(Chapter V)*

(Chapter II)
From stories to maps: translating participatory scenario narratives into spatially explicit information

(Chapter IV)
Land-use intensification causes the spatial contraction of woody-plant based ecosystem services

(Chapter III)
Spatial predictions for the distribution of woody plant species under different land-use scenarios

(Chapter V)
Future ecosystem services provision under land-use change scenarios

KEY FINDINGS:

- LULC changed markedly under the four land-use scenarios, with strong distinctions between the individual scenarios. Substantial LULC changes were associated with large-scale land-use scenarios.
- Large-scale agricultural scenarios would result in strong losses of biodiversity and ES provisioning. However, changes were not uniform across the landscape.
- Large-scale agricultural scenarios would lead to the contraction of woody plant based ES that are concentrated and spatially coincided in the forest.
- Under the 'Coffee and conservation' scenario, forest could be relieved of the pressure to provide woody plant based ES.
- Large-scale agricultural scenarios (either for coffee or crop production) caused major trade-offs with other potential ES.
- 'Coffee and conservation' scenario showed a positive change for woody-plant biodiversity and ES provision.

SYNTHESIS

- Spatially explicit maps of biodiversity and ecosystem services at different scales could improve decision-making.
- Land-use scenarios of large-scale agricultural intensification would cause both biodiversity and ES loss.
- The creation of a new biosphere reserve: A sustainable future trajectory for southwestern Ethiopia.

Fig. 2. Overview of the dissertation project. A brief description at the top, followed by the overarching goal and specific objectives as addressed in individual chapters. Key findings and synthesis are presented at the bottom.

Summary of included chapters

In **Chapter II**, we translated four plausible future narrative socio-economic land-use scenarios developed by participatory scenario planning into spatially explicit land-use scenario maps. First, we created a baseline map of current LULC from Sentinel satellite image of 10m resolution using supervised image classification. Then, we established translation rules based on the scenario narratives key variables, biophysical elements and distance from forest edge. To produce scenario maps, we processed the baseline map into four different spatially explicit scenarios of LULC in the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs, Natural Capital Project) (Sharp et al. 2018)) proximity-based scenario generator. Finally, we assessed changes at landscape scale and at groups of kebeles of different social-ecological characteristics.

The results showed that in the baseline, forests covered more than half (53%) of the study region, whereas arable land and pasture represented 26% and 11% of the LULC, respectively. LULC changed markedly under the four land-use scenarios, with strong distinctions between the individual scenarios. ‘Gain over grain’ scenario showed a strong decrease in arable land and pasture, while under the ‘Mining green gold’ scenario, almost half of the landscape in the current and future coffee growing altitudes were converted to coffee plantations. In the ‘Food first’ scenario, arable land expanded and covered more than half of the landscape. Under the ‘Coffee and conservation’ scenario, there were relatively few changes in the landscape from the baseline compared to the other scenarios. Changes were not uniform across kebele groups for all scenarios. The spatially explicit land-use scenario maps produced were highly effective in visualizing LULC components related to the previously generated scenarios, and as such, they underlined the internal consistency of any given scenario. Developing an approach that translates narrative scenarios into maps further advances scenario research toward being a proactive tool because it provides spatially explicit information which can help stakeholders and decision makers plan for the future.

This chapter provides a methodological contribution to scenario research by exploring how to translate narratives to spatially explicit information. Besides, it also provides an empirical contribution to future land-use mapping which can be used to model ecological and social outcomes of different land-use strategies. Finally, it provides a practical contribution which could support decision makers and local stakeholders for land-use management and policy to avoid undesirable environmental and social consequences of different land-use scenarios.

In **Chapter III**, we modelled woody plant species richness, specifically, total species richness and forest specialist species richness, for the present and for the four land-use scenarios. Woody plant species were surveyed previously at 181 sites within 20m x 20m quadrants. We then joined fifteen candidate predictors identified based on our ecological knowledge of the landscape and continuous spatial data availability for the baseline and future scenarios to the woody plant species data. We used cross-validated generalized linear models. Selected models were projected out to the study region, including for the current landscape and future scenarios both in the farmland and in the forest, separately. The results for farmland and forest were merged to produce a single predicted map of the landscape. Finally, we summarized the results at the kebele level to support local decision makers.

The results showed that total species richness was higher in forest compared to farmland; forest specialist species richness was lower than total species richness overall, and forest specialists were relatively rich in forest than in farmland, and their richness increased toward the forest interior. Further, results indicate that the ‘Mining green gold’ and ‘Food first’ scenarios would result in strong losses of biodiversity, whereas the ‘Gain over grain’ scenario largely maintained biodiversity relative to the baseline. Only the ‘Coffee and conservation’ scenario, which incorporates a new biosphere reserve, showed positive changes for biodiversity which are likely viable in the long term. The creation of a biosphere reserve could maintain and improve woody plant richness in the focal region, and, by forming a connected cluster with existing reserves, would be a major step forward for sustainability in southwestern Ethiopia.

This chapter provides an empirical contribution to biodiversity research focused on modelling and mapping specific aspects of biodiversity, such as woody plants species richness for different plausible future land-use alternatives. It also provides a practical contribution which could support stakeholders and decision-makers planning a desirable future by providing spatially explicit information on the impact of different plausible land-use scenarios on biodiversity loss.

Chapter IV addresses spatially explicit maps of woody plant-based ES hotspot richness under different scenarios of land-use change. In this study, we used a comprehensive interdisciplinary dataset which draws on scenarios of landscape change, distribution data of woody plant species, household surveys on how woody plants are used as ES by local people and a high-resolution LULC map. Combining these datasets, we statistically modelled individual ES and predicted the selected models spatially for the current landscape and future scenarios to get availability of woody-plant based ES in the landscape, in farmland and forest. From predicted ES maps, ES hotspots were produced for each potential ES. Then, we calculated the richness of ES hotspots, i.e., overlaps of (combined) priority areas for different ES hotspots.

Predicted maps of individual woody-plant based ES revealed a strong effect of land-use scenarios on ES generation. In the current landscape, ‘Gain over grain’ and ‘Coffee and conservation’ scenarios, woody plant-based ES hotspots spatially coincided most notably in forest, but numerous ES hotspots also occurred within farmland. Contrary to this, intensive agricultural practices, for either cash crops or food crops, would lead to a contraction of woody-plant based ES, from a mixture of farmland and forested areas to remnant forest patches. Since local people need access to these ES, these results imply both a decrease in local accessibility to ES and increased pressure on remaining forest patches in scenarios of agricultural intensification. The effectiveness of sparing such patches from human influence in the context of this study area is questionable from a practical perspective and could have significant negative implications for biodiversity conservation and local livelihoods.

This chapter provides an empirical contribution to the debate on land sharing and land sparing in which land sparing was considered as a strategy to protect forest which, in turn, could conserve biodiversity. Land sparing in the context of this study could even increase pressure on forest and would not be practical. In addition, it contributes to research on ES provision under land sharing and land sparing strategies. Methodologically, it contributes to social-ecological systems research which focus on ES research, showing how data from different disciplines can be combined and analyzed under different plausible land-use strategies. It also provides a practical contribution which could be relevant to stakeholders and decision-makers by providing spatially explicit information of woody plant-based ES provisioning and its implication in conservation planning in smallholder-dominated landscapes of the Global South.

In **Chapter V**, we quantified and mapped the spatial distribution of potential supply of six ES (erosion control, carbon storage, woody plant richness, coffee production, crop production and livestock feed) for the current landscape and four land-use scenarios in order to understand the effect of land-use change on these potential ES. To map and quantify erosion control and carbon storage, we used the InVEST tool (Sharp et al. 2018). For woody plant richness, we used the results modeled in Chapter III. For coffee and crop production, we used the potential areas of these productions from LULC maps and average productivity from secondary data to get production maps, respectively. For livestock feed, we used area of pasture from the LULC map as the best proxy available for our study area. We analyzed changes at the landscape scale and at kebele level (the smallest administrative unit in Ethiopia).

The results show that changes in potential ES provision were strongest for land-use scenarios based on large-scale agricultural intensification. Smallholder farmers specialization using cash crops on farmland (i.e., the ‘Gain over grain’ scenario) are likely to cause less impact on potential ES compared to ‘Mining green gold’ and ‘Food first’ scenarios. Moreover, ‘Coffee and conservation’ scenario showed a relatively positive impact on potential ES provision which can be more beneficial to the local community and increase the resilience of the environment. Besides, ES changes were not uniform across the landscape for all scenarios. ES synergies and tradeoffs varied only slightly across the scenarios. Potential ES maps of land-use scenarios provide useful information which could support decision-makers and stakeholders when planning for the future of the landscape. Thus, based on our findings, the ‘Coffee and conservation’ scenario could be a viable future that could conserve the landscape ecosystems of the southwestern Ethiopia and contribute to human well-being.

This chapter provides an empirical contribution to research on potential supply of ES based on biophysical elements under different plausible land-use strategies. It also provides a practical contribution which could support stakeholders and decision-makers by its spatially explicit information and synergies and trade-offs among potential ES provisioning under different land-use scenarios that could help in land-use planning and conservation prioritization.

Synthesis

Spatially explicit maps of biodiversity and ES at different scales could improve decision-making

Envisioning the future in a structured manner (Henrichs et al. 2010) is useful to anticipate plausible consequences of current developments and plausible future alternatives on both ecosystems and society (Henrichs et al. 2010; IPBES 2016; WWF 2020). Spatially explicit information is a proactive tool which can be used for multiple purposes to support stakeholders and decision-makers to plan for the future (Peterson et al. 2003; Alcamo 2008). Here, spatially explicit land-use scenario maps that are translated from narratives developed by participatory scenario planning (Chapter II) and used to model, predict and map biodiversity and ES provide useful quantitative and spatially explicit information (Chapter III – V). These results can be used to facilitate transparent negotiation, communication, awareness raising; to stimulate discussion and creative thinking on their plausibility; and to facilitate engagement in the process of change to support better policy and decision-making at different government or administrative levels (Henrichs et al. 2010; IPBES 2016; WWF 2020).

In this dissertation, the spatially explicit information is presented at landscape scale and at kebele level so it is possible to identify spatially differentiated changes within each land-use scenarios (e.g., Chapter II, III, V). Such spatially differentiated information for individual land-use scenarios allows consideration of the desirability or undesirability of different land-use scenarios based on localized social-ecological conditions. This approach also allows decision-makers to develop spatially differentiated land-use management policies.

For instance, at the landscape scale, strong biodiversity losses were observed for large-scale agricultural intensification scenarios, i.e., the ‘Mining green gold’ and ‘Food first’. However, disaggregated results at kebele level showed the effects among kebeles were not uniform for all scenarios, and it was even more heterogeneous for the ‘Mining green gold’ scenario. In this case, kebeles at high and low elevations showed no change in biodiversity, whereas kebeles characterized by a high percentage of woody vegetation and located on intermediate elevations experienced very strong biodiversity losses (Chapter III). Similarly, potential ES maps at landscape scale (Chapter V) showed an increase in erosion control and carbon storage service. This result supports the findings of other researchers (Hylander et al. 2013; Takahashi and Todo 2013), who concluded that the presence of coffee reduces deforestation and thus also minimizes soil loss and maintains carbon storage. However, the disaggregated results of the landscape at kebele level showed that the effect of coffee presence on erosion control and carbon storage differed across the kebeles. Intensive coffee plantations led to increased soil loss and decreased carbon storage in kebeles currently dominated by forest. Similarly, in the 'Food first' scenario, potential crop production increased by more than double at landscape level, but it did not change for kebeles characterized by a complex topography not suitable for large-scale intensive farming (Chapter V). In general, elevation, topography and land cover types (such as forest, arable land and pasture) of the kebeles played a key role in disaggregated results, which revealed differences in LULC change and landscape suitability for specific crops derived diverging responses in these scenarios.

Thus, the novel methods employed to generate spatially explicit maps from participatory scenario planning developed in this dissertation can be used as a valuable input to help stakeholders and decision-makers weigh the advantages and drawbacks of different development trajectories on ecosystems and human well-being (Foley et al. 2005; IPBES 2016). These tools support stakeholders and decision-makers to move away from the reactive mode of decision-making to proactive decision-making (Henrichs et al. 2010; IPBES 2016) by sketching out the land-use realities of alternative scenarios and quantifying the tradeoffs associated with specific changes in LULC under each scenario (Chapter III – V). As such, spatially explicit information, then, provides useful opportunities for stakeholders and decision-makers to proactively manage plausible LULC changes and its related biodiversity and ES changes into a desirable condition. These context specific spatially explicit maps of the landscape, which showed LULC change (Chapter II), biodiversity distribution (Chapter III) and ES provisioning (Chapter IV, V) were further spatially disaggregated at the smaller administrative units. This could help stakeholders and decision-makers to facilitate spatially differentiated approaches to land-use management due to socio-ecological changes occurring at the landscape scale and to choose the more desirable future, namely one which conserves biodiversity and benefits human well-being in the long run.

Land-use scenarios of large-scale agricultural intensification would cause both biodiversity and ES loss

Two scenarios, ‘Mining green gold’ and ‘Food first’, are driven by large-scale monoculture agricultural expansion and intensification of coffee and cereal crop production, respectively. In both scenarios, no integration occurred of food production and biodiversity conservation, and remaining forest patches were to be spared through strict regulations limiting access for local communities (Jiren et al. 2020). These scenarios are well aligned with a government policy which intends to improve food security at the national level and to increase foreign exchange earnings from agricultural exports, generating increased food availability and improved incomes (Rahmato 2011; Keeley et al. 2014; Shete and Rutten 2015; Bachewe et al. 2018). As discussed in detail in Chapter II, both the scientific literature and government documents on large-scale agricultural expansion and intensification in Ethiopia (Keeley et al. 2014; Baumgartner et al. 2015; Bachewe et al. 2018; Moreda 2018a; Wayessa 2020) provide evidence for the plausibility of these two scenarios, which show two different types of large-scale agricultural investment.

The maps of these scenarios indicated that approximately about half of the landscape was covered by coffee plantations and intensive cereal crop production under ‘Mining green gold’ and ‘Food first’ scenarios, respectively (Chapter II). These could have the potential benefit of increasing export and boosting national food production levels (Rahmato 2014; Jiren et al. 2020). However, it might come at the expense of biodiversity, ES and local community’s access to food and ES (Chapter III-V). The modelling results for biodiversity responses revealed clear differences among all the scenarios. However, these two scenarios showed strong losses in biodiversity responses compared to other scenarios. The ‘Mining green gold’ scenario was mainly driven by the clearance of small patches of woody vegetation in farmland within future coffee elevation and by conversion of forest to large-scale coffee plantation, whereas ‘Food first’ scenario was largely due to decreased farmland heterogeneity and significant deforestation in the wake of large-scale agricultural land expansion and intensification (Chapter III).

Further, the modelling and mapping results of woody-plant based ES revealed that these scenarios would cause a displacement of woody plant-based ES from agricultural land to forested areas. The impact of these land-use scenarios on the physical distribution of woody plants made woody plant-based ES hotspot richness concentrated and coinciding spatially in the interior forest and remnant forest patches, a consequence which could very likely put pressure on and cause exploitation of the remaining forests (Chapter IV). Such LULC changes under these two scenarios could undermine the important role of forests for future biodiversity conservation and local ES provisioning, which are a critical and central part of the local community's livelihood (Schultner et al. 2021; Shumi et al. 2021). In the context of this study area, the effectiveness of sparing such forest patches from human influence for biodiversity conservation will most likely not be successful, because people are likely to go into the forest and then extract these ES from the forest out of necessity (Chapter IV). Thus, this empirical finding could contribute to the theoretical debate of land sharing vs. land sparing, calling into question some of the simplistic assumptions and lack of feedbacks in the theoretical models when applied to complex real-world social-ecological systems, especially in smallholder-dominated landscape of the Global South.

Further, the potential increase in coffee production under the 'Mining green gold' and crop production under the 'Food first' scenarios is likely to cause a decrease in other potential ES such as carbon storage, erosion control and livestock feed (Chapter V). Similar trade-offs between monoculture-based agricultural production and other potential ES have been observed for large-scale agricultural intensification across the world (e.g., Rasmussen et al. 2018; Beckmann et al. 2019; Davis et al. 2020; Kim et al. 2022). Such studies, for instance, in Southeast Asia (Appelt et al. 2022), Cambodia (Davis et al. 2015), Ethiopia (Moreda 2017) or Rwanda (Kim et al. 2022) have also consistently shown that many local stakeholders were excluded from the potential benefits of increased monoculture production and restricted from accessing vital common property resources. In addition, they lost the quantity and diversity of food and income, adversely affecting their well-being. Thus, these two scenarios are unlikely to avoid biodiversity and ES losses, and they could have a negative long-term impact on both ecosystems and human well-being.

The creation of a new biosphere reserve: A suitable future trajectory for southwestern Ethiopia

Contrary to the large-scale intensification scenarios based on land sparing strategy, 'Coffee and conservation' and the 'Gain over grain' scenarios are based on integrated land-use strategy, the land sharing approach. However, the 'Gain over grain' scenario involved the use of agrochemicals and plantations (such as *eucalyptus* and khat) on farmland which both harm the environment and human well-being in the future (Chapter III-V). For this reason, this scenario cannot provide a sustainable future trajectory for southwestern Ethiopia. The 'Coffee and conservation' scenario is driven by a sustainable land management approach in the context of a newly created biosphere reserve. Globally, biosphere reserves were launched in 1970s by UNESCO's Man and Biosphere Programme (MAB) to promote people-centered sustainable land-management approach to landscapes (Coetzer et al. 2014; Van Cuong et al. 2017). Biosphere Reserves integrate three main functions (conservation of biodiversity and cultural diversity, economic development and logistic support) in its three main zones (core areas, buffer zones and transition areas) (https://en.unesco.org/biosphere/about). The challenges, lessons learned and success stories of Biosphere Reserves are documented by several studies (Stoll-Kleemann and Welp 2008; Coetzer et al. 2014; Van Cuong et al. 2017).

The results of 'Coffee and conservation' scenario, that aimed the creation of new biosphere reserve, showed forest cover remain stable, degraded steep slopes became restored by native woody vegetation and fruit trees, resulting in a highly diversified farmland mosaic (Chapter II). Biodiversity models that emphasized on woody plant species richness (Chapter III) showed mostly positive responses for the 'Coffee and conservation' scenario compared to the other scenarios, whereas it was mostly negative effect for the large-scale agricultural intensification scenarios and slight positive responses for the 'Gain over grain' scenario. The positive effect of biodiversity responses in 'Coffee and conservation' scenario was mainly due to the heterogeneous landscape that resulted from the restoration of degraded farmland and maintained woody vegetation cover (Chapter II). As such, this scenario revealed key characteristics for biodiversity-friendly farming such as the maintenance of native vegetation, the improvement of heterogeneity and structural complexity and an avoidance of the use of agrochemicals (Perfecto and Vandermeer 2010; Fischer et al. 2013). The effect of such heterogeneous landscape created by this scenario is also reflected in the woody plant-based ES model, in which the outcome showed a more widespread distribution of woody plant-based ES across the entire landscape, indicating that forests in this scenario may be relieved from human pressure compared to the current situation and other scenarios (Chapter IV). In addition to such a positive impact on woody plant species richness and woody plant-based ES provisioning, regulating ES such as potential erosion control and carbon storage were increased under this scenario (Chapter V). Such positive responses have far-reaching positive effect on the landscape and beyond.

Despite these positive impacts, the results showed substantial decrease in potential crop production and livestock feed under this scenario (Chapter V), which could negatively affect the local well-being of the community in the short-term. This slight limitation is widely acknowledged as a challenge for integrating food production and biodiversity conservation (Kremen 2015; e.g., Mehrabi et al. 2018a). However, such short-term challenges could be substituted by a substantial increase in fruits and vegetables (Chapter II), income that could be generated from eco-tourism (Jiren et al. 2020) and increases in potential shade coffee production (Chapter V).

As such, this scenario could potentially preserve the current multifunctionality of the landscape, that absorb pressure from the remaining forest (Chapter III, IV) and thereby protect the gene pool of wild Arabica coffee through conservation of the last remaining coffee forests (Aerts et al. 2015). In addition to conservation benefits, based on the physical availability and distribution of forest and woody plants, this scenario would likely increases access to woody plant-based ES for the local community (Chapter IV), which closely depends on the ES generated from the landscape (Tadesse et al. 2014b; Ango 2018; Schultner et al. 2021; Shumi et al. 2021). This scenario reflected the idea of 'working lands conservation' (Kremen and Merenlender 2018), which support both biodiversity conservation and ES provision for humanity, thereby serving both ecosystems and human well-being for long-term social-ecological sustainability and resilience.

Thus, the creation of a new biosphere reserve could make major contributions to biodiversity conservation and human well-being in the region. It would lead to a spatially connected cluster with other biosphere reserves within southwestern Ethiopia, for example the Yayu coffee forest biosphere reserve in the north and Kaffa biosphere reserve in the south of the study area, which are both registered to UNESCO in 2010 and have similar LULC characteristic as the study area (Gole et al. 2009; NABU 2017). Aggregations of biosphere reserves are recognized as important "clusters" by the UNESCO (Urban and Beswick 2018). Especially if published guidelines for the establishment and management of successful biosphere reserves are followed (Stoll-Kleemann and Welp 2008; Van Cuong et al. 2017) as well as the challenges and opportunities facing the Yayu and Kafa biosphere reserves are considered (e.g., Beyene et al. 2020; Bires and Raj 2020; Jackson et al. 2020; Mohammed 2020), it is highly plausible that the ‘Coffee and conservation’ scenario could indeed contribute to the urgently required conservation of Ethiopian coffee forest and could represent a sustainable trajectory for southwestern Ethiopia.

Future research

In this dissertation, I showed how narrative scenarios developed by participatory scenario planning can be translated to spatially explicit land-use scenario maps. These can be used to model, predict and map woody plant biodiversity and ES provision. I have also shown how these spatially explicit land-use scenario maps can be used to map other potential ecosystem services such as regulating services (carbon storage, erosion control) and provisioning services (coffee production, crop production and livestock feed). This spatially explicit land-use scenario maps can be used for future research to model and map biodiversity of different taxa such as birds and mammals, and different potential ES such as pollination, water quality and cultural ES. Moreover, different aspects of the scenarios may manifest in different parts of the landscape. Future research could also further explore and identify which aspects of different scenarios are most desirable in different sections of the study area. Finally, the methods and approaches presented in this dissertation can be applied and replicated to a similar landscape that has similar social, environmental and economic characteristics.

Conclusion

In this dissertation, I presented how narrative social-ecological land-use scenarios can be translated to spatially explicit land-use scenario maps that could be used to evaluate different social and ecological outcomes. The dissertation highlights the need for more sophisticated and integrated social-ecological modelling of land-use change and provides a set of novel methodological steps for generating such socially robust and useful information for stakeholders. As highlighted in this framework paper the various chapters in this dissertation make a number of theoretical, methodological and empirical contributions to the developing fields of scenario planning, social-ecological systems, conservation and landscape change science. However, a key contribution, beyond those to science, is the generation of robust, useful models and maps which could potentially aid in local stakeholders and decision-makers, helping them to make informed and more sustainable decisions regarding land-use management in the rapidly changing and vitally important landscapes of southwestern Ethiopia.

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Chapter II

Chapter II

From stories to maps: translating participatory scenario narratives into spatially explicit information

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ABSTRACT

To understand future land use change, and related ecological and social impacts, scenario planning has become increasingly popular. We demonstrate an approach for translating scenario narratives into spatially explicit land use maps. Starting from four previously developed scenarios of land use change in southwestern Ethiopia we developed a baseline land use map, and rules for how to modify the baseline map under each scenario. We used the proximity-based scenario generator of the InVEST software to model the prospective land cover changes to existing forest (53%), arable land (26%), pasture (11%), and wetlands (7%), under the four future scenarios. The model results indicate that forest cover area would remain essentially the same under the "gain over grain" and "biosphere reserve" scenarios. Coffee plantations would cover almost half the landscape (49%) in the "mining green gold" scenario, whereas arable land would expand and cover more than half of the landscape (57%) in the "food first" scenario. The approach presented here integrates future land use mapping with participatory, narrative-based scenario research to assess the social-ecological outcomes of alternative futures. The translation of narratives onto maps can help researchers and stakeholders better understand and communicate potential land use changes, and facilitate a more spatially nuanced approach to managing or adapting to broad scale socioeconomic changes. Our study constitutes a methodological contribution to the management of land use change, as well as a tool to facilitate transparent policy negotiation and communication at local, government, and NGO levels.

Keywords: InVEST; landscape; land use and land cover maps; narrative scenarios; plausible futures; spatially explicit land use scenarios; translation rules

INTRODUCTION

Changes in land use are pervasive in rural areas around the world and impact both ecosystems and people (Millennium Ecosystem Assessment 2005, Haines-Young 2009, Quintas-Soriano et al. 2016). Identifying potential changes in land use helps decision makers to assess the sustainability of alternative future pathways. To assess plausible futures for a particular landscape, many scenario mapping exercises have downscaled regional or global scenarios to a more localized level (Gaffin et al. 2004, Verburg et al. 2006, Frame et al. 2018). Such downscaling provides consistent high-resolution land use and land cover (LULC) for assessing aggregate impacts over large spatial extents. However, the usefulness of such approaches at fine scales may be limited by the lack of context regarding local realities. In contrast, a growing number of social-ecological scenarios are being generated directly in local landscapes together with stakeholders (reviewed by Oteros-Rozas et al. 2015). Localized scenario development facilitates a detailed understanding of the specific dynamics of a place and the contextually relevant drivers of change. However, participatory approaches that generate localized scenarios typically result in the development of narratives. Although such narratives are useful for engaging diverse stakeholders, they lack the spatially explicit, quantitative information provided by downscaled higher level scenarios. To overcome this limitation, in this paper, we demonstrate an approach to translating scenario narratives into spatially explicit LULC maps for four scenarios developed in southwestern Ethiopia. Before presenting our approach, we provide short background reflections on land use change, scenario planning, and existing attempts to turn scenario narratives into maps.

Within a given landscape, LULC change results from a combination of direct and indirect social and ecological drivers (Díaz et al. 2019). Human-driven LULC change is a key driver of the loss of biodiversity and ecosystem services (e.g., Sala et al. 2000, Díaz et al. 2019). From an ecological perspective, LULC change causes biodiversity loss by altering the composition, distribution, abundance and functioning of biological diversity and related processes (e.g. Millennium Ecosystem Assessment 2005, Díaz et al. 2019). LULC change is projected to further intensify, resulting in increasingly higher loss of biodiversity (Sala et al. 2000, Powers and Jetz 2019). The impact of LULC on biodiversity depends on the intensity of change, the configuration of land use patterns, and the spatial distribution of natural biophysical variables (Zebisch et al. 2004). From a social perspective, LULC change and the resulting loss of biodiversity also alter the generation and provisioning of ecosystem services, that is, the benefits that people obtain from the environment (Millennium Ecosystem Assessment 2005).

To understand future LULC change, and related ecological and social impacts, scenario planning has become increasingly popular. Scenario planning can help decision makers to proactively consider uncertainty when choosing among policy alternatives (Peterson et al. 2003, Shoyama and Yamagata 2014, IPBES 2016). Scenario planning combines various tools and techniques to develop plausible and internally consistent descriptions of alternative futures (Peterson et al. 2003, IPBES 2016). Although scenario planning does not eliminate uncertainties about the future, it can provide a means to represent current knowledge in the form of consistent conditional statements about the future; thereby providing a rational and reflected basis for improved decision making (Alcamo et al. 2008).

One useful level at which to analyze LULC change is the landscape scale (Wu 2013). Landscapes, in turn, can be analyzed as social-ecological systems, that is, systems in which social and ecological variables are closely interlinked (Fischer et al. 2017). In the context of analyzing landscape-level changes in social-ecological systems, participatory scenario planning has become increasingly popular. Oteros-Rozas et al. (2015), for example, reviewed 23 cases in which participatory scenario planning was used to investigate land use change related futures of social-ecological systems. Participatory scenario planning has been used to explore alternative development trajectories in semi-arid Tanzania (Enfors et al. 2008); to identify changes in ecosystem services in an agricultural landscape in South Africa (Malinga et al. 2013); and to develop plausible scenarios focusing on food security and biodiversity conservation in Ethiopia (Jiren et al. 2020).

Narratives of alternative futures generated in participatory approaches are powerful because they encapsulate the views of diverse stakeholders (Alcamo et al. 2008, Mallampalli et al. 2016, Fischer et al. 2018). This, in turn, can lay the foundation for developing a shared vision for the future (Alcamo et al. 2008, Mallampalli et al. 2016, Nieto-Romero et al. 2016), facilitate social learning, and generate novel ideas for how to achieve a desired and sustainable future (Butler et al. 2014, Booth et al. 2016, Jiren et al. 2020). However, scenario narratives typically result in generalized statements of what the future might look like, rather than quantitatively explicit LULC maps. The precise way in which a given scenario plays out at fine scales, in turn, depends on locally specific social-ecological conditions (Hanspach et al. 2014). The generalized nature of narratives thus makes it difficult to analyze quantitatively the implications of LULC (e.g., on different species and ecosystem services), thereby limiting the extent to which decision makers might engage with such scenarios.

To date, few studies have translated qualitative narrative scenarios at the landscape level into quantitative LULC maps (but see Kok and van Delden 2009, Swetnam et al. 2011, Booth et al. 2016, Kohler et al. 2017). The "story and simulation" approach (Alcamo 2008), in which scenarios are first defined by experts and other stakeholders and subsequently translated into quantitative parameters that can be fed into simulation models, has been most commonly used to couple qualitative and quantitative scenarios (Mallampalli et al. 2016). Given the usefulness of scenario mapping and the growing popularity of participatory scenario planning in social-ecological research (Oteros-Rozas et al. 2015), additional work is needed on how to translate narratives into maps.

Here, we present such an approach. We focus on rural southwestern Ethiopia, for which we had earlier developed four alternative narrative scenarios of social-ecological change (Fischer et al. 2018, Jiren et al. 2020). Our approach combines the extraction of key variables and trends from stakeholder-derived storylines of the future, their translation into quantitative spatial variables, and the subsequent spatial projection of changes to present land cover under different scenarios.

The contribution of our study is twofold. First, from a methodological perspective, our approach is useful to integrate LULC mapping with participatory, narrative-based scenario development. Second, from an applied perspective, our approach helps to better understand plausible LULC change in southwestern Ethiopia, which is valuable for regional-level stakeholders, planners, and policy makers.

METHODS

Study area

The study area consists of three districts or *woredas* (Gera, Gumay, and Setema) in Jimma Zone, Oromia Region, southwestern Ethiopia, with a total area of about 2800 km^2. Based on Ethiopia's multi-level governance system, woredas are districts that are further subdivided into *kebeles*, where each kebele contains a minimum of 500 households (Fig. 1). Southwestern Ethiopia is a globally recognized biodiversity hotspot (Mittermeier et al. 2011, Bellard et al. 2014), with large areas of Afromontane forests (Hylander et al. 2013a). It is also the place where Arabian coffee (*Coffea arabica*) originates (Senbeta and Denich 2006). Coffee here is traditionally grown in forests under the shade of native trees (Jena et al. 2012). The landscape consists of a forest-agricultural mosaic (Ango et al. 2014, Dorresteijn et al. 2017) that provides multiple ecosystem services to the local population. These ecosystem services are key to local people's livelihoods and well-being (Shumi et al. 2019a).

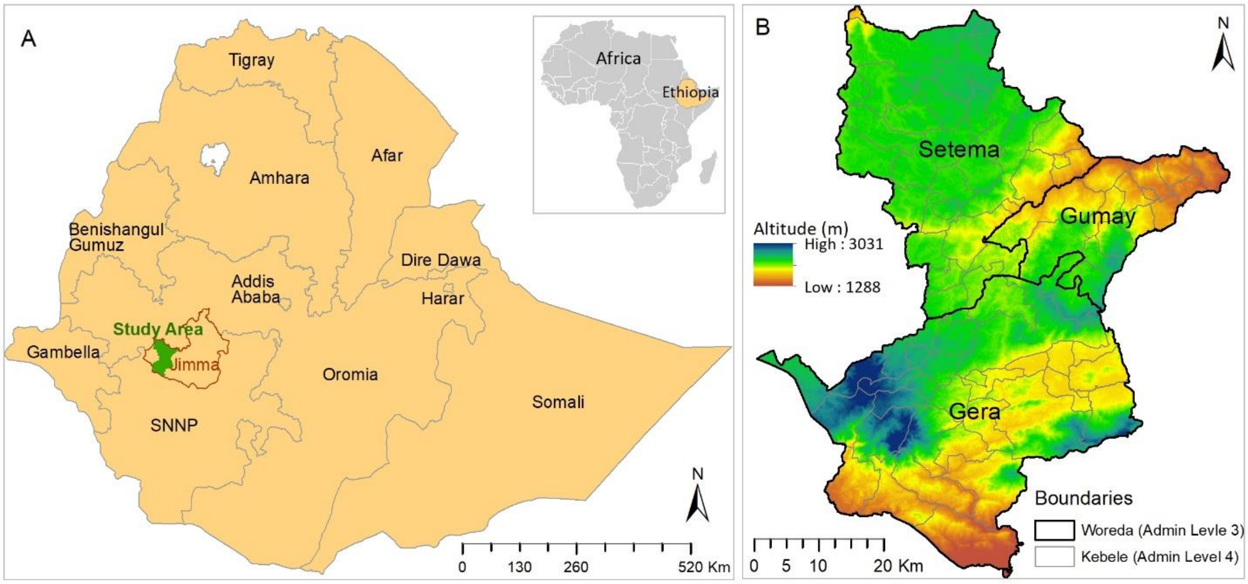

Fig. 1. Map of (A) the location of the study area in Jimma Zone, Oromia, Ethiopia; and (B) a detailed view of the three woredas targeted here, including kebeles boundaries and altitude (from ASTER DEM).

From narratives to maps: translation steps

Our methodological approach to translating scenario narratives into maps consisted of five key steps, which we outline in detail below. Briefly, first, four narrative scenarios were developed (for details, see Fischer et al. 2018, Jiren et al. 2020). Second, we created a baseline map of current land uses from satellite imagery. Third, based on the scenario narratives, we developed rules for how to modify the baseline map under each scenario. Fourth, we used the proximity-based scenario generator of the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software

(Sharp et al. 2018) to produce maps of the four scenarios. Fifth, we assessed how each of the scenarios affected kebeles of different socioeconomic and biophysical characteristics.

Step 1: Development of the narrative scenarios

Prior to this paper, we had developed four qualitative narrative scenarios (Fig. 2) through participatory scenario planning, which involved 35 stakeholders from different organizations and local community groups (for details, see Fischer et al. 2018, Jiren et al. 2020). Those 35 stakeholders, in turn, were based on an in-depth analysis of the stakeholder network in the study area (Jiren et al. 2018). The scenarios considered a wide range of plausible environmental, social, and economic changes, and are briefly summarized below and in Appendix 1, Table A1.10. The time period for the scenarios was 20 years, from 2020 to 2040.

“A. Gain over grain”: local cash crops

This scenario prioritizes farmers’ specialization and commercialization to boost development, while traditional food cropping is abandoned in favor of cash crops. The cash crops are coffee, the stimulant drug khat (*Catha edulis*), and fast-growing trees, mostly eucalyptus. The landscape largely consists of intensively managed coffee forests interspersed with khat and tree plantations. Farmers are encouraged to increase coffee production through newly created coffee plantations. Eucalyptus plantations primarily target degraded areas and marginal land. Khat plantations on former farmland are intensively managed. Farmland biodiversity is dramatically reduced because of intensive management and habitat simplification. The production of food crops is limited: little space remains for cultivating cereal crops, and only a few farmers maintain small cereal fields. To maximize the limited food production, the most fertile land is preferentially used for farming.

“B. 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. The landscape consists of intensively managed high-yielding coffee plantations, and relatively little food is produced. Smallholder land, communal land, and forests conducive for coffee investment have been transferred to capital investors for the creation and expansion of coffee plantations. The use of non-native species for coffee shading is common. Local farmers are left to farm marginalized areas unsuitable for large scale coffee plantations, e.g., steep hillslopes.

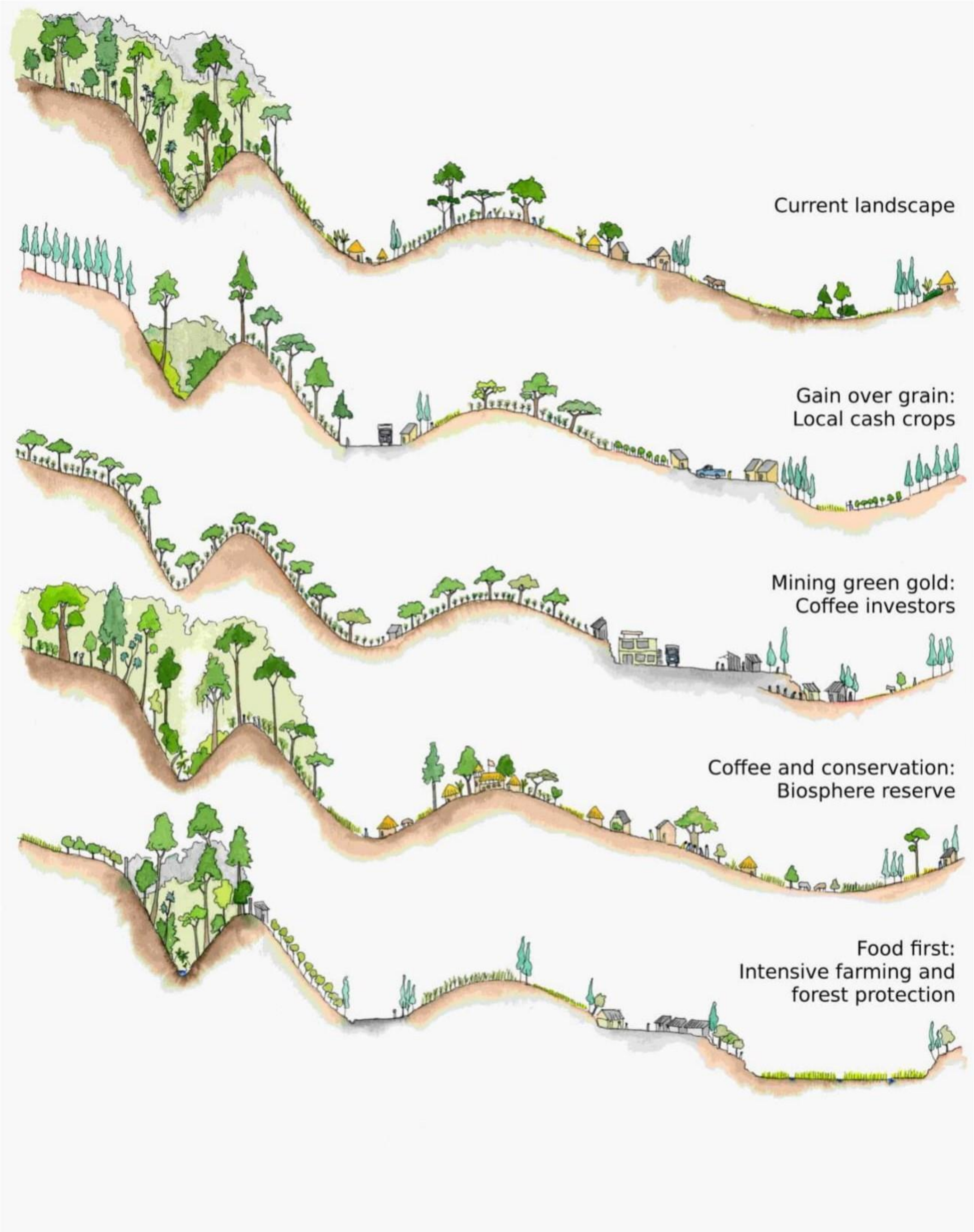

Fig. 2. Landscape view at present and in the four scenarios (reproduced from Jiren et al., 2020). The current landscape consists of a mosaic of food crops, cash crops, pasture, forest, and settlements. The “Gain over grain” scenario describes a landscape covered by different cash crops, whereas intensive coffee plantations dominate the landscape in “Mining green gold”. The “Coffee and conservation” scenario is similar to the current landscape in that different crops, trees, and

settlements co-exist. The "Food first" scenario consists of a landscape dominated by intensively produced food crops, where forest is spared from human activities.

"C. Coffee and conservation": a biosphere reserve

This scenario is based on a more balanced land use approach. Because of the failure of conventional agriculture and increasing global interest in sustainably grown coffee, a biosphere reserve has been established that combines sustainable agriculture, environmentally friendly coffee production, and tourism. The landscape is a diversified mosaic of forest and farmland and consists of a core zone with unused natural forest; a buffer zone for low-intensity production of local coffee, wild honey, and other forest products; and an outer zone with interspersed cropland, pastures, and tree plantations. Livestock production and communal grazing take place much like at present, and people grow fruits and vegetables as well as grains. Sustainable resource management and improved soil and water conservation are practiced to revert environmental degradation.

"D. Food first": intensive farming and forest protection

This scenario is driven by the impacts of climate change on food and coffee production. Climate change has made coffee production less viable in southwest Ethiopia, and food production has been failing elsewhere in the country. Large amounts of food are now produced in the southwest through intensive, large-scale agriculture, which involves extensive land consolidation, including the clearing of woody vegetation and the expansion of cropland on flatlands and drained wetlands. The landscape is dominated by cereal crop production. Intensified fruit and vegetable plots, as well as pastures for beef fattening and commercial beef production are also present, especially on steep slopes. The remaining patches of natural forest are strictly protected, and the local community is not permitted to access them.

Step 2: Current land cover mapping

In this step, we mapped the current extent of biophysically distinct land use and land cover classes. Characterization of land cover details began with 10 meter Sentinal-2 satellite imagery (channels 2, 3, 4, and 8) (freely downloaded from https://scihub.copernicus.eu/) from January 2019. January 2019 was chosen because it was the latest cloud free image available for the study area to clearly differentiate the different land cover features. This imagery in combination with ground control points were used to produce the current extent of land use and land cover. Over 1000 ground control points (GCPs) were gathered from different sources (Table 1).

Table 1. Ground control points (GCPs) used for image classification and accuracy assessment with their sources. Out of 159 GCPs from primary fieldwork, 107 GCPs were collected during the previous project called "Identifying Social-Ecological System Properties Benefitting Biodiversity and Food Security (SESyP)" (Shumi et al. 2018, 2019b), and 52 GCPs were collected by the first author of this paper during a short field trip in February 2020.

Land cover	For classification			For verification (accuracy assessment)
	Primary field data	GCPs from Google Earth	Total GCPs	GCPs from Google Earth
Woody vegetation	49	17	66	312
Pasture	46	16	62	120
Arable land	46	20	66	192
Grazed wetland	2	55	57	75
Cultivated wetland	2	40	42	100
Settlement	8	30	38	77
Total	159	178	338	876

We used supervised image classification (Lillesand et al. 2004) to generate six land cover classes of the study area. We used this method of land cover mapping because we had extensive knowledge and data on the area, including having collected many ground control points. Supervised image classification was conducted using ArcGIS Desktop 10.6.1. Signatures from GCPs were taken and analyzed for all primary land cover types identified for mapping, namely woody vegetation, arable land, pasture, cultivated wetland, grazed wetland, and settlement. These signatures were given as input to the maximum likelihood classification method (Lillesand et al. 2004, Gil et al. 2011, Patil et al. 2012). Accuracy assessment of the image classification was done via stratified random sampling (following Olofsson et al. 2014) using 876 points collected from Google Earth. The resulting 10-m pixel classification included fine-scale variation in land covers, e.g. scattered woody vegetation within farmland.

Following the initial classification into six main classes, we increased the thematic resolution of land covers in the landscape. For terrain slope, based on the literature, we used a threshold of 30% in slope to classify flat versus steep areas (Henricksen et al. 1988). To differentiate between levels of farmland heterogeneity, we ran a moving window analysis in Fragstats v4.2.1 to determine the percent woody vegetation within a 200-m radius. We then classified farmland as of low heterogeneity (< 5% woody vegetation), medium heterogeneity (5–20% woody vegetation), and high heterogeneity (> 20% woody vegetation). We classified altitude into five ranges (< 1300 m, 1300–1500 m, 1500–2100 m, 2100–2300 m, > 2300 m), mainly based on the altitudes where coffee growing is viable, both for currently suitable ranges (Senbeta and Denich 2006, Hylander et al. 2013b, Tadesse et al. 2014, Shumi et al. 2018) and a projected future altitudinal shift until 2040 (Moat et al. 2017). Distance from the edge of the forest was used to differentiate between interior forest and edge forest, where forest beyond 150 m from the edge was classified as interior (Shumi et al. 2019b). Combining these different criteria then allowed us to add thematic layering options to the land use map.

In addition to the land uses in Table 1, which were generated by using satellite image and GCPs only, we added four additional land uses (coffee plantations, eucalyptus plantations, khat, and fruits and vegetables) to the baseline map based on their current approximated locations because they were not directly visible from satellite imagery. Although their present location was not precisely known, we made assumptions based on our knowledge of the study area where these land uses were most likely to occur. For coffee plantations, we assumed that current coffee plantations are found at the edges of flat forested areas, in altitude ranges from 1500 to 2100m, within 1 km distance from a road, and only in kebeles confirmed by local administrators as having coffee plantations. For eucalyptus plantations, we assumed these to occur close (within 1 km) to tin roofed houses, and in small patches of woody vegetation measuring less than 0.25 ha. This was based on findings that most villagers plant eucalyptus around their homesteads (Takahashi and Todo 2017) and that eucalyptus is mostly found in woodlot areas outside natural forest (Ango et al. 2014). We further assumed that khat was found very close to homesteads on arable land, and only in kebeles mentioned by local administrators to contain khat. We therefore allocated small patches of arable land (less than 0.25 ha) adjacent to tin roofs to khat. Similar to khat, for fruits and vegetables we allocated small patches (less than 0.25 ha) of cultivated wetland close to homesteads. Woody vegetation was divided into two classes reflecting whether it occurred as part of the forest (where woody vegetation patches > 1 ha) or was dispersed as farmland woody vegetation (where woody vegetation patches < 1 ha). Settlement was assigned to agglomeration of tin roofs in the study area. We divided settlement into towns and rural settlements. Based on the location of the three administrative towns of the three woredas (CSA 2007) agglomerated tin roofs were assigned to towns, whereas the remaining agglomerated tin roofs in the study area were taken as rural settlement. The final baseline map thus generated contained 12 land use and land cover classes: forest, woody vegetation in farmland, arable land, pasture, cultivated wetland, grazed wetland, coffee plantation, eucalyptus plantation, khat, fruits and vegetables, rural settlement, and towns.

Step 3: Translation of narrative rules into qualitative spatially explicit rules

To translate narratives into maps, we defined rules that allowed specific land use/cover types to be converted under the scenarios. For this, we started by extracting and summarizing from each scenario narrative qualitative rules that could be converted into spatially explicit rules. For each land cover class in the baseline map, a set of rules were generated that governed how and where changes could occur. These rules were established using a combination of land cover classes, biophysical elements (such as slope, heterogeneity, and altitude), and distance from forest edge. Thus, the rules were context specific, that is, they were dependent on local conditions and importantly, they were directly linked to the narratives of the scenarios developed with local stakeholders for that specific area. Hence, although our general approach for deriving locally relevant rules is transferable to other places, the specific rules are not transferable.

We developed transition rules so that all land use transitions occurring in the narrative scenarios could be expressed via spatially explicit quantitative rules. The rules were derived via iterative discussions within the author team, with the central aim being that they were plausible based on known dynamics of LULC change and consistent with the scenario narratives (Table 2, Appendix 1 Tables A1.1–A1.4.). In all scenarios, towns and rural settlements expanded at annual rates of 5.4% and 1.8%, respectively (World Bank 2015, Schmidt et al. 2018). In addition, in the “B. Mining green gold” scenario, grazed and cultivated wetlands remained unaltered compared to the baseline because such wet areas are unsuitable for coffee plantations (Teketay 1999).

Table 2. Examples of key rules for the conversion of LULC using for the translation of qualitative narratives into quantitative rules under different scenarios. Details of the rules of conversion can be found in the supplementary material (Supplementary Tables S1, S2, S3, and S4, for "Gain over grain", "Mining green gold", "Coffee and conservation" and "Food first" scenarios, respectively).

Scenarios	Qualitative rules identified from the narrative scenarios	Quantitative rules that detail the original land use/cover to be converted
Gain over grain	Farmers are encouraged to increase coffee production on farmland – arable land.	44% (27,500 ha) of flat, arable land at future coffee-producing altitudes (1500-2300m) was converted to coffee plantation.
Gain over grain	Intensively managed khat plantations are established on former farmland.	21% (13,000 ha) of flat, arable land at below- and above-coffee altitudes (<1500m and >2300m) was converted to khat plantation.
Gain over grain	Fast-growing trees (mainly monocultures of eucalyptus plantations) primarily target degraded areas or marginal land.	85% (9,800ha) of steep, arable land was converted to eucalyptus plantation.
Mining green gold	Large areas of smallholder arable land conducive for coffee investment have been transferred to capital investors for the expansion of large-scale intensive coffee plantations.	75% (47,400 ha) of flat, arable land at future coffee producing altitudes (1500-2300m) was converted to coffee plantation .
Mining green gold	Large areas of farmland woody vegetation were converted into intensively managed shade coffee plantations, often using non-native shade tree species.	60% (2,800 ha) of farmland woody vegetation in flat areas at future coffee producing altitudes (1500-2300m) was converted to coffee plantation.
Mining green gold	Large areas of natural forest conducive for coffee investment has been transferred to capital investors for the expansion of largescale intensive coffee plantations.	50% (74,400 ha) of forest at future coffee producing altitudes (1500-2300m) was converted to coffee plantation.
Coffee and conservation	The landscape consists of a core zone of unused natural forest and a buffer zone for low intensity production.	Forests were maintained as in the baseline.
Coffee and conservation	The landscape consists of an outer area to a core and buffer zones of forests with a mosaic of cropland, pastures, and tree plantations.	Flat and steep arable land with high woody vegetation was maintained as in the baseline.
Coffee and conservation	Livestock production and communal grazing are maintained.	Flat and steep pastures on with high woody vegetation was maintained as in the baseline
Food first	Large-scale land consolidation, including clearing of woody vegetation and cropland expansion.	Flat, arable land remains as in the baseline.
Food first	Farming has been mechanized as much as possible with government-owned tractors being available for hire to work the large stretches of cropland in the flat areas.	Farmland woody vegetation on flat areas (3,900 ha) was converted to arable land.
Food first	Modern agriculture almost completely replaced traditional small-scale farming.	Flat pasture (27,900 ha) was converted to arable land.

Step 4: Scenario maps generation

To produce scenario maps, we processed the baseline map into four different spatially explicit scenarios of LULC in the InVEST proximity-based scenario generator based on the established conversion rules. InVEST is a tool designed to inform decisions about natural resource management by providing information about how changes in ecosystems are likely to lead to changes in the flows of benefits to people (Sharp et al. 2018). The proximity-based scenario generator in InVEST is a model that is used to create a set of contrasting LULC maps that convert land cover in different spatial patterns (Sharp et al. 2018). For all scenarios, conversion of the original, to-be-converted land covers started from those edges that were most proximate to the target, newly established land cover. For every scenario, we identified the area of the original and target land covers, in hectares, that needed to be replaced. For this, we intersected the spatial layers of land use and land cover, slope, percent woody vegetation, and altitude in ArcGIS ArcMap 10.6.1 version using the “Intersect tool” in “Spatial analysis” that creates an output layer with table columns of those mentioned layers. Then, we calculated the area for this new layer using the “Calculate geometry tool.” When different conversion rules were competing for the same land cover type, we defined priorities based on the logics of the narrative scenarios regarding which conversion was more important. The resulting, altered land cover map was then used to run the next iteration of conversions that were of lower priority. For a single scenario, we thus ran multiple iterations before the final land cover map was completed. The InVEST model outputs were then visualized in a geographic information system (GIS), where we also extracted summaries of area changes for each land cover compared to the baseline map.

Step 5: Contrasting future changes between groups of kebeles

Finally, we clustered kebeles into distinct groups to summarize the changes occurring in the spatially explicit LULC scenario maps. Such summarizing of changes by kebele groups was meaningful because (a) the large number of kebeles (n = 67) rendered the presentation of LULC for each kebele unpractical, (b) many kebeles may share characteristics and therefore might be similar in the changes that occur, and (c) aggregating LULC across a woreda (regardless of the diversity of kebeles within the woreda), or the entire study area, would potentially obscure important spatial patterns of LULC change.

We used nine baseline variables, i.e. present conditions, to group kebeles according to their social-ecological characteristics. Three of these variables, the areas of woody vegetation, pastures, and arable land, were used as proxies for their overall agro-ecological makeup and were generated from the satellite imagery. Three other variables, the present levels of khat, eucalyptus, and honey production, were chosen because of their key importance for the livelihoods of the local community and were gathered from interviews with local experts. Khat and eucalyptus were estimated based on their area coverage in hectares, whereas honey production was estimated in kilograms. Two variables, mean altitude and kebele remoteness, were important general variables that might influence a range of social-ecological characteristics. Mean altitude was calculated from ASTER digital elevation model with 30-m resolution (obtained from https://asterweb.jpl.nasa.gov/gdem.asp; NASA/METI/AIST/Japan Spacesystems and U.S./Japan ASTER Science Team 2009). A remoteness index was calculated as the weighted overlay analysis using equal weights of the distance from the nearest town, the distance from the nearest road, and the subjective perception of local stakeholders classifying kebeles into one of five remoteness classes. Last, we considered wealth as an important socioeconomic variable and therefore also calculated a wealth index for the study area based on the ratio of tin roofs (identified from satellite imagery) to households in a kebele.

We used hierarchical clustering of these nine variables to identify distinct groups of kebeles and visualized the resulting groups in a dendrogram, with the number of groups selected based on group interpretability and approximately balanced group sizes (Oberlack et al. 2019, Rocha et al. 2020, Schultner et al. 2021). Specifically, based on the scores in the variables, we calculated a distance matrix using Ward's method and visualized by "dendextend" package in R. We also visualized the kebeles and groups in two-dimensional non-metric multidimensional scaling (NDMS) to confirm the groupings (Galili 2015).

RESULTS

Land cover maps

In the baseline, forests covered more than half (53%) of the study region. Arable land and pasture represented 26% and 11% of the land cover, respectively. Cultivated wetland made up 5%, while grazed wetland, farmland woody vegetation, eucalyptus plantations, coffee plantations, fruit and vegetable plots, khat, and settlements together covered the remaining 5% of the region (Table 3).

The result of the overall accuracy assessment for the baseline was 86.3%, and the kappa coefficient was 0.82. Figure 3 presents the map of the baseline together with the four scenarios.

Table 3. Percent LULC under the scenarios.

	Percentage of land cover for baseline and scenarios (in %).				
Land cover	**Current landscape**	**Gain over grain**	**Mining green gold**	**Coffee and conservation**	**Food first**
Arable land	26.5	9.3	9.4	12.3	57.4
Coffee plantation	0.3	12.3	49.1	0.3	0.0
Cultivated wetland	4.9	4.6	4.9	4.6	0.0
Eucalyptus plantation	0.1	6.4	0.0	0.0	0.1
Farmland woody vegetation	1.7	1.5	0.7	9.8	0.0
Forest	52.9	52.8	26.4	52.9	35.2
Fruits and vegetables	0.1	0.1	0.1	8.6	2.1
Grazed wetland	0.9	0.9	0.9	0.9	0.0
Khat	0.1	6.0	0.1	0.1	0.1
Pasture	11.1	4.2	6.6	8.5	3.3
Settlement	1.3	1.3	1.3	1.3	1.3
Towns	0.3	0.6	0.6	0.6	0.6

Kebele groups

The kebeles were clustered into four groups based on their baseline social-ecological characteristics. The first cluster of kebeles, the “pasture-cropland group,” contained 17 kebeles and was characterized by the high availability of pasture and arable land. This group had the lowest cover of woody vegetation and low levels of coffee forest, khat, and eucalyptus. A second cluster of 19 kebeles, the “khat-cropland group,” had a distinctly high availability of khat and arable land and was located at higher altitudes. This group had low coffee forest availability and the lowest wealth index. A third cluster of 18 kebeles, 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. Finally, a fourth cluster of 12 kebeles, the “accessible-wealthy group,” had large extents of eucalyptus plantations, and was relatively accessible and wealthy. Figure 4 shows the hierarchical clustering presented as a dendrogram. We cross-checked the dendrogram with NDMS ordination for the groups, but we did not include the graph.

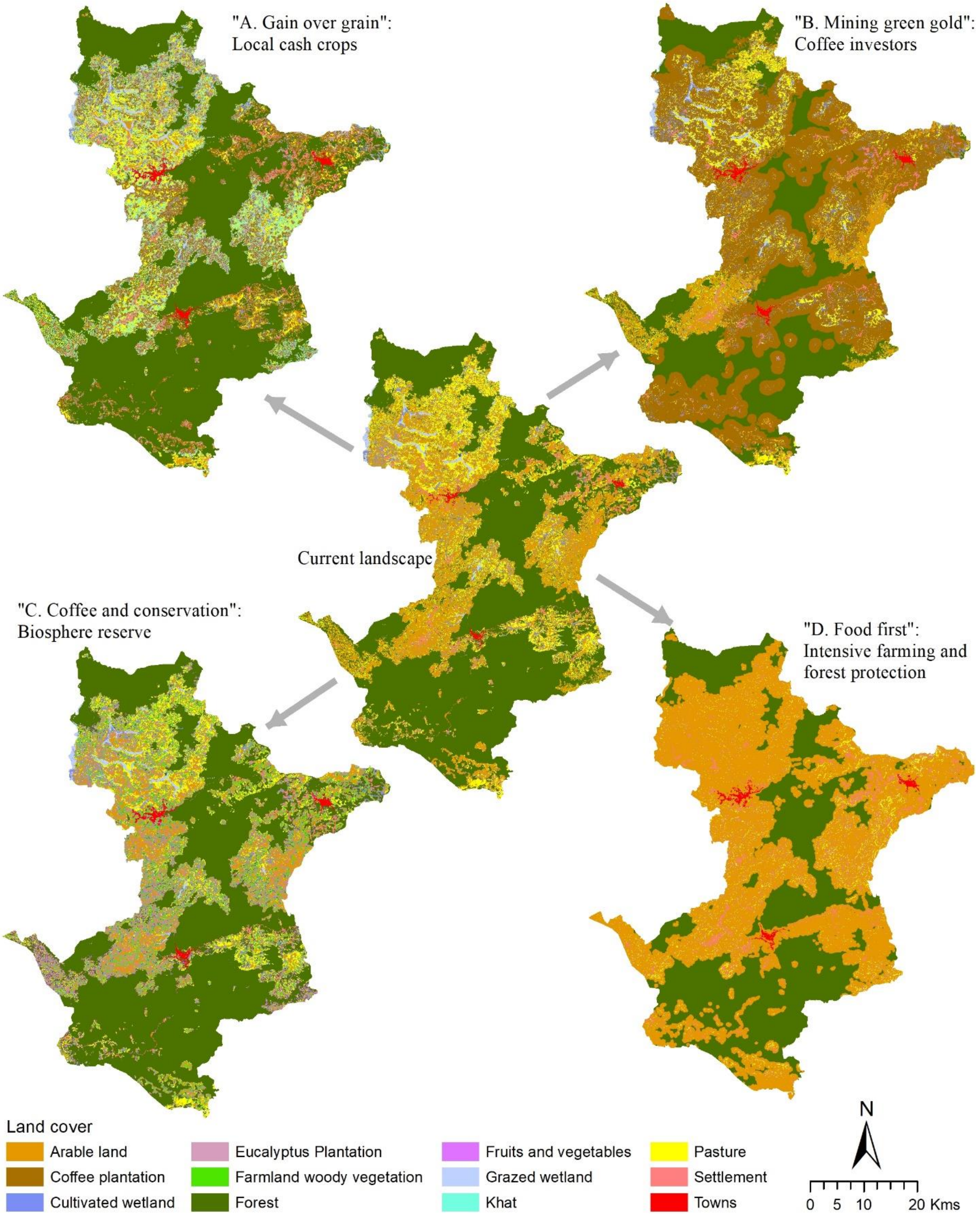

Fig. 3. Baseline and scenario land cover maps. Arrows in the map indicate the plausibility of land cover change from the current landscape to the four scenarios.

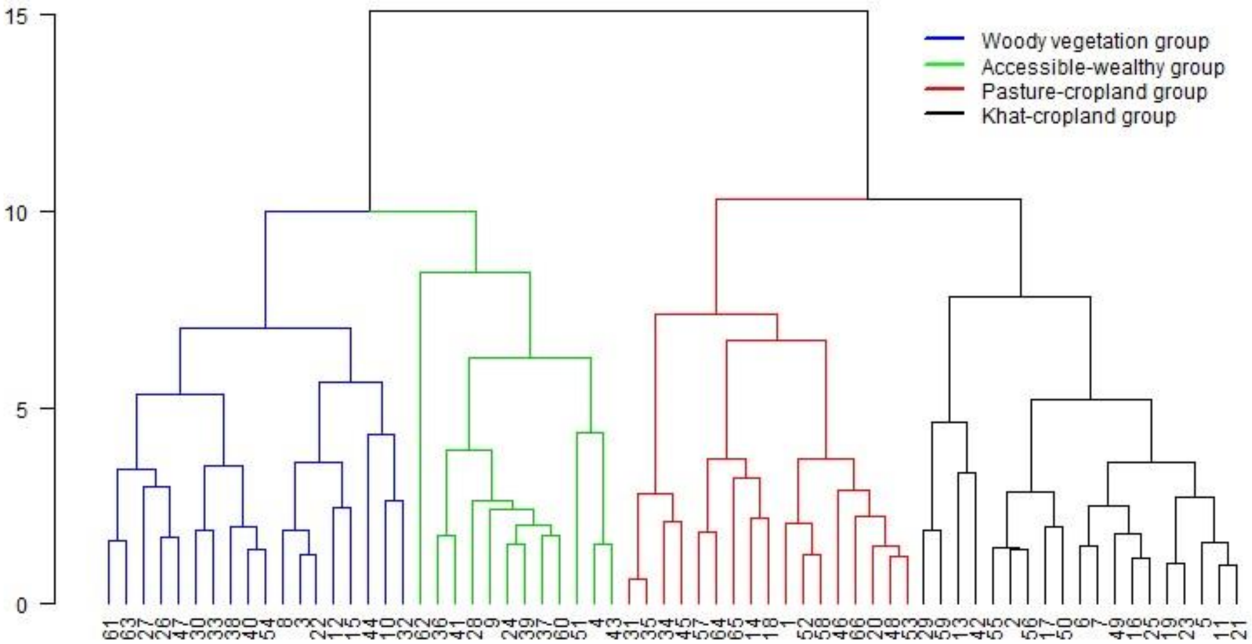

Fig. 4. Cluster dendrogram of kebele groups, where branch colors indicate the groups (light blue = “woody vegetation group”, light green = “accessible-wealthy group”, light red = “pasture-cropland group”, and light black = “khat-cropland group”).

Spatially explicit scenario maps

Land cover changed markedly under the four different future scenarios, with strong distinctions between the individual scenarios. Figure 5 shows the total LULC under each scenario, whereas Table 3 summarizes the LULC proportional to the baseline extent of land covers under each scenario. Notably, however, changes in a given scenario did not occur uniformly across the study region but differed between kebele groups. Along with general changes, we therefore also present differences between the kebele groups. Note that all land cover and land cover changes in the following summaries are rounded to the nearest percent(age).

“A. Gain over grain”: local cash crops

The “A. Gain over grain” scenario was characterized by strong changes in arable land and pasture, which decreased by 17% and 7%, respectively. Coffee plantations increased by 12%, and eucalyptus plantations and khat plots by 6% each (Fig. 5 and Supplementary Table A1.5). Forest cover, farmland woody vegetation, and cultivated wetland all showed slight decreases due to settlement (both rural and urban) expansion. Under this scenario, forest cover remained essentially unchanged, accounting for approximately half of the landscape (53%). Outside the forest, the landscape was covered by coffee plantations (12%), followed by arable land (9%), eucalyptus plantations (6%), and khat (6%; Table 3).

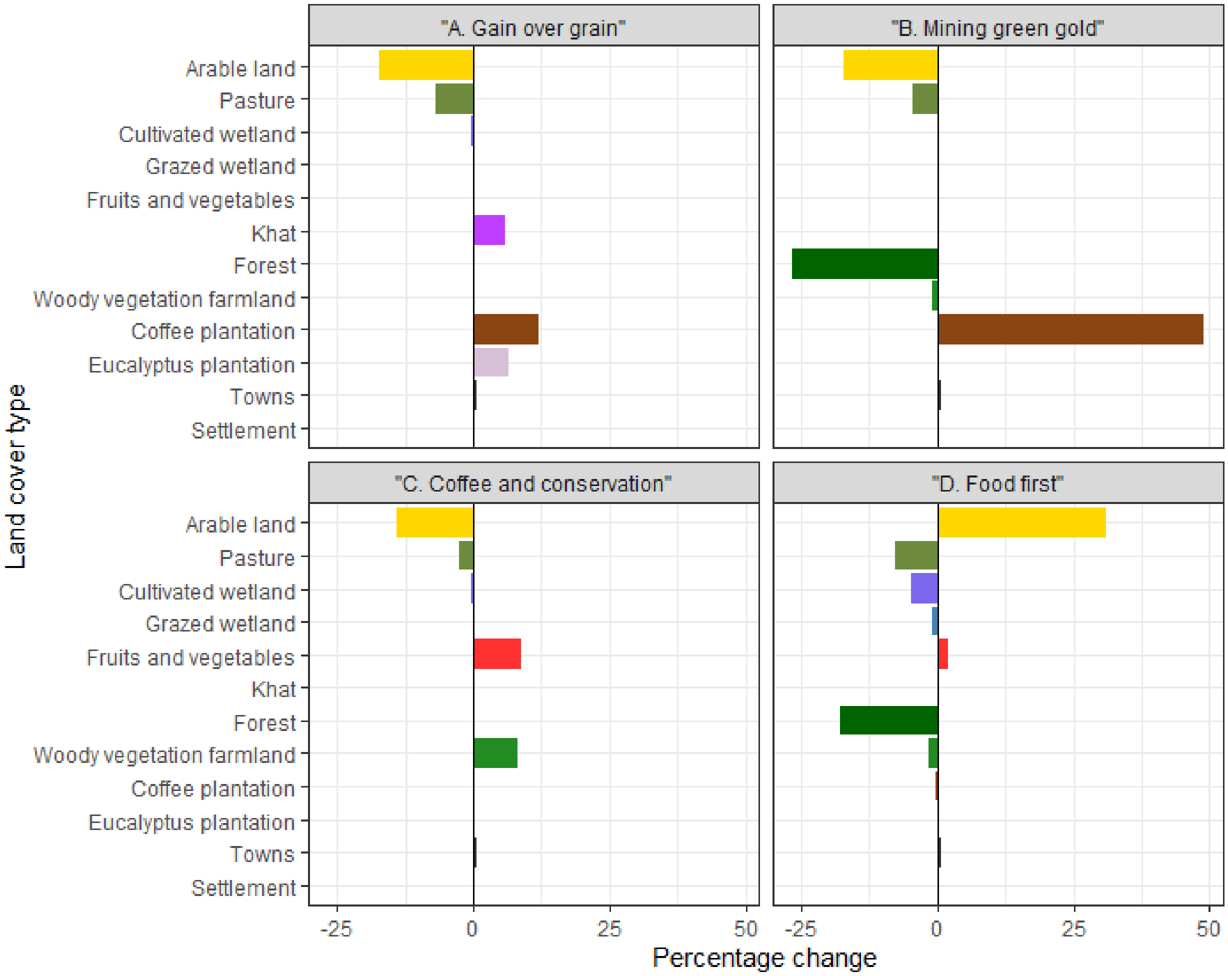

Fig. 5. Percentage change of land cover types under the scenarios.

Under the "A. Gain over grain" scenario, the greatest changes occurred in the khat-cropland kebeles, which were originally characterized by a large extent of arable land and relatively high altitude. As indicated in Figure 6 and Table A1.6, arable land decreased by 46%, whereas it decreased by 34%, 25%, and 17% in the pasture-cropland, accessible-wealthy, and woody vegetation kebeles, respectively. Coffee plantations increased by 20% in both the khat-cropland and accessible-wealthy kebeles, whereas they increased by 15% and 12% in pasture-cropland and woody vegetation kebeles, respectively. Eucalyptus plantations increased by 12% in both the pasture-cropland and khat-cropland kebeles, while they increased by 5% in woody vegetation and accessible-wealthy kebeles. Similarly, khat increased by 14% and 12% in pasture-cropland and khat-cropland kebeles, respectively. There was a small increase in khat in the woody vegetation accessible-wealthy kebeles groups of 2% and 3%, respectively. Details of percentage changes by kebele groups are provided in a Supplementary Table A1.6.

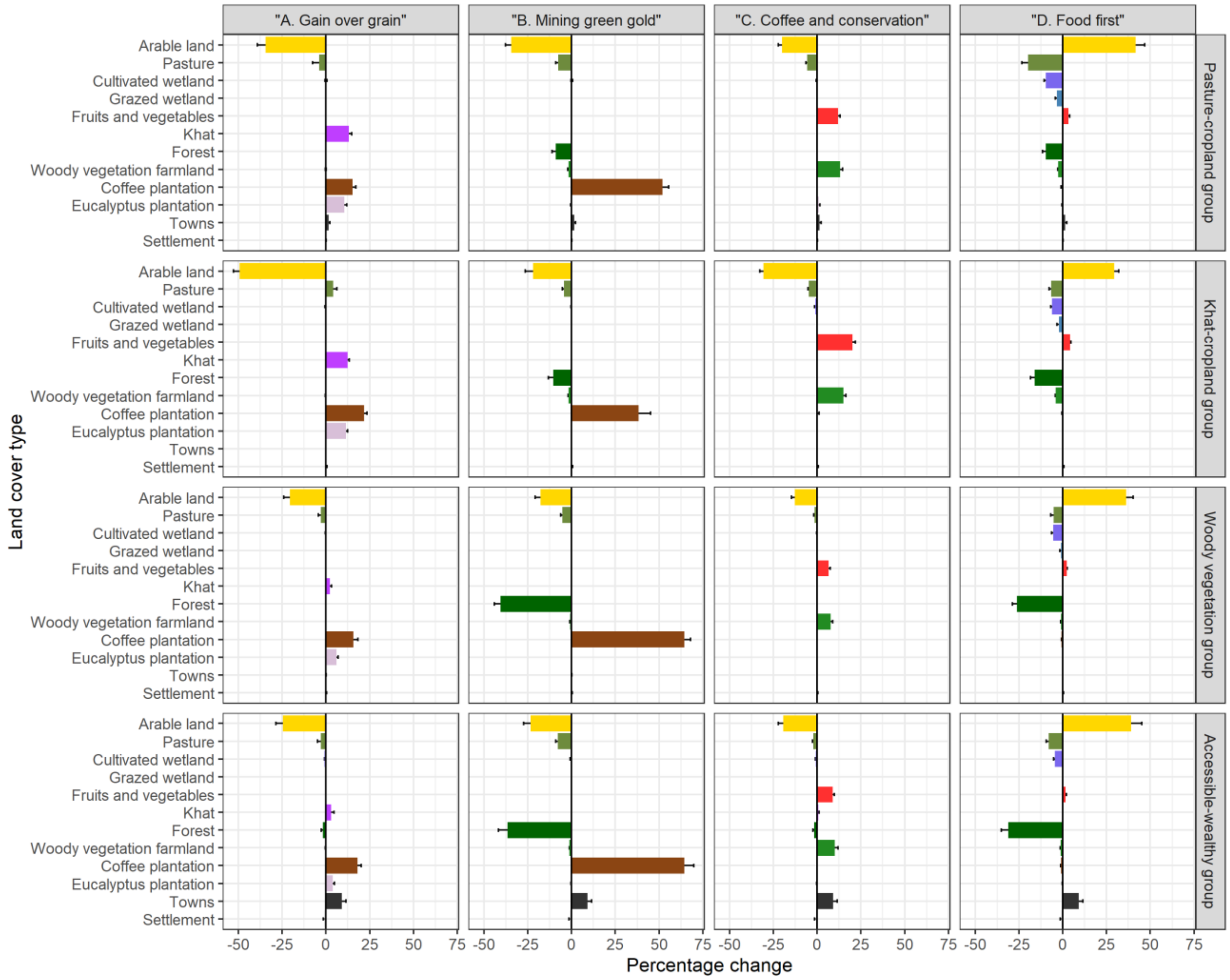

Fig. 6. Comparison of the results of percentage changes showing means and standard errors of changes in land covers by scenarios and kebele groups. Kebele groups are listed on the right side as the pasture-cropland group, khat-cropland group, woody vegetation group, and accessible-wealthy group.

"B. Mining green gold": coffee investors

Because this scenario promoted large-scale coffee investment, almost half of the landscape (49%) was converted to intensive coffee plantations. Twenty-seven percent of forest, 17% of arable land, 5% of pasture, and 1% of farmland woody vegetation most suitable for coffee growing were converted to plantations (Fig. 5 and Table A1.5). These conversions took place not only in the current coffee growing altitudes up to 2100 m but up to 2300 m reflecting the predicted shift in suitable areas due to climate change (Moat et al. 2017). In contrast, lower altitudes (1300–1500 m) lost coffee because of increasing climatic unsuitability. Under this scenario, the remaining land cover mainly constituted forest cover (26%), followed by arable land (9%), and pasture (7%; Table 3). Forest, arable land, and pasture decreased by 27%, 17%, and 5%, respectively (Table A1.5).

All kebele groups experienced significant increases in coffee plantations. However, the accessible-wealthy kebeles and woody vegetation kebeles saw the strongest increases in coffee plantations by 72% and 61%, respectively. The khat-cropland kebeles saw an increase in coffee plantations by 41% (Table A1.7 and Fig. 6). Arable land decreased in all kebele groups. However, the strongest decrease occurred in pasture-cropland kebeles of 33%, whereas there was a smaller decrease in the woody vegetation kebeles of 14%. Similarly, forest showed a strong decrease in both the woody vegetation and accessible-wealthy kebeles (41%), with a smaller decrease in the pasture-cropland kebeles (8%). Details of changes of LULC by kebele groups are presented in Table A1.7 and Figure 6.

"C. Coffee and conservation": a biosphere reserve

Here, there were relatively few changes in the landscape from the baseline compared to the other scenarios. Forest cover remained stable, occupying more than half of the landscape (53%) followed by arable land (12%). Farmland woody vegetation increased and constituted 10% of the landscape, followed by fruits and vegetables (9%) and pasture (8%; Table 3). This scenario saw an increase in landscape heterogeneity (Fig. 3). Arable land and pasture decreased by approximately 14% and 3%, respectively. In contrast, fruits and vegetables and farmland woody vegetation increased by 9% and 8%, respectively (Table A1.5).

All kebele groups experienced slight changes under this scenario. However, the khat-cropland kebeles and the pasture-cropland kebeles saw strong increases in farmland woody vegetation of 13% and 14%, respectively. Similarly, fruits and vegetables increased by 12% and 20% in the khat-cropland and pasture-cropland kebeles, respectively. Details are presented in Figure 6 and Table A1.8.

“D. Food first”: intensive farming and forest protection

The “D. Food first” scenario was characterized by a strong change to most of the land covers in the landscape. Arable land expanded and covered more than half of the landscape (57%). The remaining proportion of the landscape was mainly covered by forest (35%), followed by pasture (3%) and fruits and vegetables (2%). Wetlands, farmland woody vegetation, and coffee plantations were lost to arable land (Table 3). This scenario created a more homogenous landscape dominated by arable land and patches of forest (Fig. 3). Arable land increased by 31%. Contrary to this, forest and pastureland decreased by 18% and 8%, respectively (Fig. 5 and Table A1.5). Pasture in this scenario was mostly restricted to steep slopes.

All kebele groups experienced increases in arable land. However, pasture-cropland and accessible-wealthy kebeles saw a stronger expansion of arable land by 40% and 44%, respectively, whereas both the khat-cropland and woody vegetation kebeles saw an increase of 32%. There were strong decreases in forest area in the accessible-wealthy kebele group (33%), while there was a smaller decrease (19%) in forest cover in the khat-cropland kebeles (Fig. 6 and Table A1.9).

DISCUSSION

We presented a structured approach for translating narrative scenarios of future landscape changes into maps. Based on key variables that we extracted from the alternative narration lines of four future scenarios that were previously developed in a participatory scenario planning process, we established quantitative rules that made future landscape changes spatially explicit. Starting from a baseline map of present land uses, we applied a set of rules to generate land use maps for the scenarios. Below, we reflect on our approach, explore some of the general and specific insights we gained from the mapping, and discuss the plausibility of each of the generated maps.

The objective of scenario research is "to move away from the reactive mode of decision making" (IPBES 2016:3). In many cases, however, scenario development stops with the generation of narrative scenarios. The approach presented here integrates future land use mapping with participatory, narrative-based scenario research as a way to assess alternative future social-ecological scenario outcomes. Although narratives may speak well to some stakeholders, e.g., local people, some stakeholders are likely to find maps more useful. Turning scenario narratives into maps thus provides additional opportunities for stakeholders and decision makers to proactively manage plausible LULC changes, biodiversity, and ecosystem services rather than simply allowing for their ongoing degradation. Crucially, the generation of context specific, but still spatially explicit maps of LULC change may help facilitate more nuanced and spatially differentiated approaches to managing or adapting to broad scale socioeconomic changes occurring at the landscape scale.

The results of our spatially explicit land use scenario maps revealed the contrasts of narratives that resulted from participatory scenario planning. As Peterson et al. (2003) argued, the central idea of scenario planning is to consider a variety of possible futures that include many of the important uncertainties in the system rather than to focus on the accurate prediction of a single outcome. The maps can also lend key support to societal envisioning processes by sketching out the land use realities of alternative objectives, and quantifying the trade-offs associated with specific changes in land use and land cover (Verburg et al. 2015). In our study, such changes and the plausibility of the generated maps were assessed at the landscape level as well as, for each scenario, for groups of kebeles with different characteristics.

One scenario focused on cash crops (coffee, khat, and fast-growing trees) grown by local smallholders ("A. Gain over grain"). Under this scenario, the map showed decreases in arable land and pasture by 17% and 7%, respectively (Table A1.5). Land use change impacted arable land and pasture in particular, because the local community focused on producing cash crops instead. At the national level, such changes are plausible; existing evidence indicates that cash crops such as coffee and khat are increasingly being produced by smallholder farmers. Coffee is the country's back bone in earning foreign exchange. About 44% of the coffee produced is exported, and about 98% of coffee in Ethiopia is produced by smallholder farmers (Dharmendra Kumar et al. 2014). Khat is an evergreen tree grown for the production of leaves that are used as a stimulant (Feyisa and Aune 2003), and it is mainly cultivated by smallholder farmers (Feyisa and Aune 2003, Gessesse Dessie 2013, Gebrehiwot et al. 2016). Land used for khat production in Ethiopia has increased rapidly in recent years (Cochrane and O'Regan 2016) replacing cereal production (Feyisa and Aune 2003), and increasingly dominating homegardens (Gebrehiwot et al. 2016). The main reasons for khat expansion are diminishing land availability, land fragmentation, declining soil productivity, a decrease in government subsidies to buy fertilizer and quality seeds for food crop production, high cash return, and low risk of theft and wildlife damage (Gessesse Dessie 2013, Gebrehiwot et al. 2016). Fast growing trees, especially eucalyptus, are also increasingly popular among smallholder farmers to generate cash. Several studies in Ethiopia have indicated that there is a recent uncontrolled expansion of eucalyptus in the country (FAO 2011, Zegeye 2010, Jaleta et al. 2016, 2017), including into smallholder croplands (FAO 2011, Jaleta et al. 2016). Multi-purpose use, fast growth, and high rates of return have made eucalyptus a preferred species by smallholder farmers (Teketay 2000, Jagger and Pender 2003). In combination, strong expansions of coffee, khat, and eucalyptus into farmland are thus highly plausible in general; our map shows one particular way in which such expansion could realistically play out in southwestern Ethiopia.

The "C. Coffee and conservation" scenario focused on sustainable land management in the context of a newly created biosphere reserve. Here, the map showed an increase in farmland woody vegetation by 8% (Table A1.5). Degraded steep slopes became restored by native woody vegetation as well as fruit trees, resulting in a highly diversified farmland mosaic. Forest cover remained stable compared to the current situation. Geographically, our study area is located in a biodiversity hotspot area (Mittermeier et al. 2011) in between two biosphere reserves, the Yayu and Kafa reserves. In the north, the study area borders onto the Yayu coffee forest biosphere reserve, which was registered by UNESCO in 2010. It covers 167,021 ha and has a similar land cover composition to our study area (Gole et al. 2009). Similarly, in the south, our study area borders onto the Kafa biosphere reserve. This was also registered in 2010, and covers an area of 744,919 ha with habitat types also similar to our study area (NABU 2017). In approximate terms, our modeled LULC map of the biosphere scenario thus showed a similar profile as the two existing biosphere reserves in the region. Placing an additional biosphere reserve in the region is especially plausible because aggregations of biosphere reserves are recognized as important "clusters" by

UNESCO (for example, Gouritz Cluster Biosphere Reserve located in South Africa; Urban and Beswick 2018). By considering general well-established factors underpinning the success of biosphere reserves (Van Cuong et al. 2017), as well as by learning from the challenges and opportunities facing the Yayu and Kafa biosphere reserves, a new biosphere reserve with diverse land cover types seems to stand good chances of successful implementation.

The other two scenarios, “B. Mining green gold” and “D. Food first,” were both based on large-scale agricultural investment and involved large-scale land acquisition or consolidation. Under the “B. Mining green gold,” which seeks to produce coffee for export to increase foreign exchange (Jiren et al. 2020), about half of the landscape (49%) was covered by coffee plantations, resulting from the conversion of about 27%, 17%, 5% of forest, arable land, and pasture, respectively (Table 3 and Table A1.5). Similarly, in the “D. Food first” scenario map, more than half of the landscape was covered by intensive cereal crop production. Under this scenario, strictly protected forest covered about 35% of the landscape, whereas about 5% of the remaining landscape was covered by pasture, fruits and vegetables, and settlements (Table 3).

Both the scientific literature and Ethiopian government documents indicate the plausibility of these two scenarios, which show two different types of large-scale agricultural investment. Since 2005, through its Growth and Transformation Plan (GTP), the Ethiopian government has promoted large-scale agricultural investment as a major part of its overall development strategy to make Ethiopia a food-secure, middle-income country by 2025 (Keeley et al. 2014, Bachewe et al. 2018) through foreign exchange earnings from agricultural exports, generating increased food availability, improved incomes via employment on commercial farms, and better infrastructure (Keeley et al. 2014, Moreda 2018). Case studies have been conducted on large-scale agricultural investment in different parts of the country, such as in Gambella region (Keeley et al. 2014, Baumgartner et al. 2015), in Benishangul Gumz region (Moreda 2017), and in Bakko Tibbe of Oromia region (Wayessa 2020). These case studies found that, contrary to the government’s expectation, the investments have often threatened both ecosystems and livelihood of local communities, depriving local communities from accessing vital common property land resources, causing land dispossession, displacement of farmers, and environmental destruction. Notably, some of the high profile cases of agricultural investment such as the Karuturi Global Ltd. farm project in Bakko Tibbe have already failed (Wayessa 2020); here, however, the land has been returned to the federal land bank for other potential investors (Moreda 2018). Thus, despite the limited success, official commitment to supporting agricultural investment projects appears to be unchanged (Rahmato 2014, Moreda 2018). Extensive land cover change to support more industrial land use practices, as indicated in our scenario maps, thus seems entirely plausible.

At the landscape level, substantial changes were associated with large-scale investment scenarios ("B. Mining green gold" and "D. Food first"), where about half of the landscape was covered by intensively managed coffee plantations or arable land, respectively. In contrast, under the "A. Gain over grain" and "C. Coffee and conservation" scenarios, LULC changed less. In both of these scenarios, wetlands and forest cover were sustained, while arable land and pasture showed a slight decrease in both scenarios. Smallholder coffee plantations, khat, and fast-growing trees increased in the "A. Gain over grain," while farmland woody vegetation and fruits and vegetables increased under the biosphere scenario. A gain in farmland woody vegetation in the "C. Coffee and conservation," in turn, would likely have major positive effects on biodiversity and ecosystem services.

The impact of scenarios differed significantly across the different types of social-ecological systems within the study area, as identified by the four kebele groups. Our results show that the four types of kebeles experienced differentiated changes under each scenario. For instance, as indicated in Figure 6, pasture-cropland kebeles were least affected by the "C. Coffee and conservation" scenario. The khat-cropland kebeles were more sensitive to the changes under the "A. Gain over grain" scenario, while the changes for these kebeles under the other three scenarios were less sensitive. Woody vegetation kebeles were most affected by the "B. Mining green gold" scenario, while they were relatively less altered by the "A. Gain over grain" and "C. Coffee and conservation" scenarios. Similar to the woody vegetation, the accessible-wealthy kebeles showed pronounced change under the coffee investment scenario. The combined use of spatial mapping and of social-ecological systems characteristics (Oberlack et al. 2019, Rocha et al. 2020) to identify spatially differentiated changes within each scenario, is therefore potentially a very useful tool. It allows consideration of both the sensitivity to, and the (un)desirability of, different scenarios based on localized social-ecological conditions. Based on such assessment, spatially differentiated polices may be developed to mitigate or encourage certain LULC change trajectories.

Notwithstanding the benefits and usefulness of translating narrative scenarios into maps (discussed above), there are also limitations. Most importantly, we acknowledge that our maps in their present form cannot capture important changes in ecological aspects, such as biodiversity loss, or social aspects such as social cohesion, equity, and food security. Other authors have noted similar challenges resulting from simplification of quantitative scenarios during translations (e.g. Kok and van Delden 2009, Booth et al. 2016), such that narratives and maps should best be consulted in combination.

The method introduced in this paper could be improved further by including stakeholders in the definition of the rules of land cover change. This, in turn, may further increase buy-in by stakeholders into the final outputs. In our case, we acknowledge that we were not able to involve stakeholders in setting the translation rules, and this could be a possible limitation of our work. However, the original narratives were co-generated with stakeholders; and the translation rules used were based on in-depth iterative discussions within the project team, who had collectively worked for multiple years (and with local stakeholders) in the study area. Finally, future research could link spatially explicit maps of plausible LULC change (such as those generated here) to spatially explicit models of biodiversity loss or resource appropriation and their impacts on issues of equity and food security.

CONCLUSION

Our spatially explicit land use scenario maps were highly effective in visualizing land use and land cover components related to the previously generated scenarios, and as such, they underline the internal consistency of any given scenario. The maps thus can be used as a valuable input to help stakeholders weigh the pros and cons of different development trajectories, which is a key benefit of using scenarios in general. Developing an approach that translates narrative scenarios into maps further advances scenario research toward being a proactive tool, because it provides spatially explicit information that can help stakeholders and decision makers plan for the future.

Until this work, to the best of our knowledge, within Ethiopia, no studies have translated narrative storylines into spatially explicit land use scenarios. Our study thus represents a methodological development that can be used as a starting point or proof of concept to be replicated in different landscapes elsewhere, and that could also be scaled up to the regional or national level. Through the generation of spatial maps of plausible futures of southwestern Ethiopia, our study also constitutes a useful practical contribution for stakeholders in management and policy, as well as a tool to facilitate transparent negotiation and communication at local, government, and NGO levels. Last, the results can also be used for further research to model ecological and social outcomes in spatially explicit ways across the four scenarios.

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Supplementary materials

Supplementary Table S1. Rules for conversion of land uses/covers under Scenario I: Cash crops

Qualitative rules identified from the narrative scenarios	**Quantitative rules that detail the original land use/cover to be converted**
Farmers are encouraged to increase coffee production on farmland – arable land	44% (27,500 ha) of flat, arable land at future coffee-producing altitudes (1500-2300m) was converted to coffee plantation.
Farmers are encouraged to increase coffee production on farmland – (pasture) and new coffee plantations may stabilize local climate	25% (7,000 ha) of flat, pasture at future coffee-producing altitudes (1500-2300m) was converted to coffee plantation.
Intensively managed khat plantations are established on former farmland	21% (13,000 ha) of flat, arable land at below- and above-future coffee altitudes (<1500m and >2300m) was converted to khat plantation.
Intensively managed khat plantations are established on former farmland	13% (3,600 ha) of flat, pasture at below- and above-future coffee altitudes (<1500m and >2300m) was converted to khat plantation.
Fast-growing trees (mainly monocultures of eucalyptus plantations) primarily target degraded areas or marginal land	85% (9,800ha) of steep, arable land was converted to eucalyptus plantation.
Tree plantations are mostly monocultures of eucalyptus, but also other fast-growing trees	85% (5,400 ha) of flat, pasture of medium heterogeneity (5%-20%) and at above-future coffee altitudes (>2300m) was converted to eucalyptus plantation.
Tree plantations are mostly monocultures of eucalyptus, but also other fast-growing trees	85% (2,800 ha) of steep, pasture was converted to eucalyptus plantation.
To ensure that sufficient food is still grown (and not only cash crops), the most fertile land should be used for farming	Flat, arable land of low heterogeneity (< 5%) and at high altitude (>2300m) remains the same as in the baseline.
To ensure that sufficient food is still grown (and not only cash crops), the most fertile land should be used for farming	Flat, pasture with low heterogeneity (<5%) and at above-coffee altitudes (>2300m) remains the same as in the baseline.
To ensure that sufficient food is still grown (and not only cash crops), the most fertile land should be used for farming	Cultivated and grazed wetlands remain the same as in the baseline.
Forest degradation slowed down because farmland can provide important tree-related ecosystem services	Farmland woody vegetation remains the same except those affected by settlement expansion.

Supplementary Table S2. Rules for conversion of land uses/covers under Scenario II: Mining green gold

Qualitative rules identified from the narrative scenarios	**Quantitative rules that detail the original land use/cover to be converted**
Large areas of smallholder arable land conducive for coffee investment has been transferred to capital investors for the expansion of largescale intensive coffee plantations.	75% (47,400 ha) of flat, arable land at future coffee producing altitudes (1500-2300m) was converted to coffee plantation.
Large areas of farmland woody vegetation were converted into intensively managed shade coffee plantations, often using non-native shade tree species.	60% (2,800 ha) of farmland woody vegetation in flat areas at future coffee producing altitudes (1500-2300m) was converted to coffee plantation.
Large areas of natural forest conducive for coffee investment has been transferred to capital investors for the expansion of largescale intensive coffee plantations.	50% (74,400 ha) of forest at future coffee producing altitudes (1500-2300m) was converted to coffee plantation.
Endemic trees and shrubs might be lost, including wild coffee and traditional shade tree species	Forest remains in altitude ranges not suitable for future coffee producing (<1500m, and >2300m).
Endemic trees and shrubs might be lost, including wild coffee and traditional shade tree species	Farmland woody vegetation in steep areas and on altitudes not suitable for coffee (<1500m, and >2300m) remains as farmland woody vegetation.
The landscape is largely transformed to a coffee production zone, with monocultures of high yielding improved coffee cultivars.	45% (12,600 ha) of flat, pasture at future coffee producing altitudes (1500-2300m) was converted to coffee plantation.
Local farmers are left to farm marginalized areas unsuitable for largescale coffee plantation such as on steep hills	Flat, arable land but on low altitude (<1500m) and very high altitude (>2300m) remain as arable land as in the baseline.
Local farmers are left to farm marginalized areas unsuitable for largescale coffee plantation such as on steep hills	Flat, pasture but on low altitude (<1500m) and very high altitude (>2300m) remain as pasture as in the baseline.
As intensified coffee plantations have expanded into farmland, very little land is left for crop production.	Steep, arable land remain arable land as in the baseline.
As intensified coffee plantations have expanded into farmland, very little land is left for crop production.	Steep, pasture remain as in the baseline.

Supplementary Table S3. Rules for conversion of land uses/covers under Scenario III: Biosphere reserve

Qualitative rules identified from the narrative scenarios	**Quantitative rules that detail the original land use/cover to be converted**
The landscape consists of a core zone of unused natural forest, a buffer zone for low intensity production of local coffee, wild honey and other forest products.	Forests were maintained as in the baseline.
The landscape consists of an outer area to a core and buffer zones of forests with a mosaic of cropland, pastures, and tree plantations.	Flat and steep arable land with high woody vegetation was maintained as in the baseline.
Livestock production and communal grazing are maintained	Flat and steep pasture with high woody vegetation was maintained as in the baseline.
People grow Fruits and vegetables in their home gardens	1/3rd (33% or 24,670 ha) of flat, arable land with low and medium heterogeneity was converted to fruits and vegetables.
Diversified landscape: diversification involving crops, forest products and ecotourism	1/3rd (25% or 2,706 ha) of steep, arable land with low and medium heterogeneity was converted to fruits and vegetables.
Sustainable resource management and improved soil and water conservation can revert environmental degradation	1/3rd (33% or 1,800 ha) of steep, arable land with low and medium woody vegetation remaining from fruits and vegetables was converted to farmland woody vegetation.
Forest cover and trees in farmland mitigate negative aspects of climate change	1/3rd (33% or 11,200 ha) of flat, arable land with low and medium woody vegetation remaining from fruits and vegetables was converted to farmland woody vegetation.
Farmland biodiversity recovered and high forest biodiversity	1/3rd (33% or 7,600 ha) of pasture with low and medium woody vegetation were converted to farmland woody vegetation.

Supplementary Table S4. Rules for conversion of land uses/covers under Scenario IV: Food first

Qualitative rules identified from the narrative scenarios	**Quantitative rules that detail the original land use/cover to be converted**
Large scale land consolidation, including clearing of woody vegetation and cropland expansion	Flat, arable land remain as in the baseline.
Farming has been mechanized as much as possible with government owned tractors being available for hire to work with the large stretches of cropland in the flat areas	Farmland woody vegetation on flat areas (3,900 ha) was converted to arable land.
Modern agriculture almost completely replaced traditional small scale farming	Flat, pasture (27,900 ha) was converted to arable land.
Flat areas including drained wetlands are dominated by large cereal fields	Grazed and cultivated wetlands were converted to arable land.
Hills and steeper slopes used for intensified fruits and vegetables, commercial bee keeping and beef fattening	50% (5,600 ha) of steep, arable land was converted to fruits and vegetables.
Hills and steeper slopes used for intensified fruits and vegetables, commercial bee keeping and beef fattening	50% (360 ha) of steep, farmland woody vegetation was converted to fruits and vegetables.
Hills and steeper slopes used for intensified fruits and vegetables, commercial bee keeping and beef fattening	50% (5,600 ha) of steep, arable land was converted to pasture.
Hills and steeper slopes used for intensified fruits and vegetables, commercial bee keeping and beef fattening	50% (360 ha) of steep, farmland woody vegetation was converted to pasture.
Hills and steeper slopes used for intensified fruits and vegetables, commercial bee keeping and beef fattening	Steep, pasture (around 3,290 ha) remain as in the baseline.
Remaining patches of natural forest are put under strict protection	50% (74,400 ha) of forest remain as forest under strict protection.
Growing coffee is unviable in most parts of southwestern Ethiopia	No coffee plantation, those available was converted to arable land.

Supplementary Table S5. Percentage of LULC changes by scenarios (in %).

	Scenarios			
LULC	**Gain over grain**	**Mining green Gold**	**Coffee and Conservation**	**Food First**
Arable land	-17.1	-17.0	-14.1	30.9
Coffee plantation	12.0	48.8	0.0	-0.3
Cultivated wetland	-0.3	-0.1	-0.3	-4.9
Eucalyptus Plantation	6.3	0.0	0.0	0.0
Farmland woody vegetation	-0.2	-1.0	8.1	-1.7
Forest	-0.1	-26.5	0.0	-17.7
Fruits and vegetables	0.0	0.0	8.6	2.1
Grazed wetland	0.0	0.0	0.0	-0.9
Khat	5.9	0.0	0.0	0.0
Pasture	-6.9	-4.5	-2.6	-7.9
Settlement	0.1	0.1	0.1	0.1
Towns	0.6	0.6	0.6	0.6

Supplementary Table S6. LULC changes by kebele groups for Cash crop scenarios (in %).

LULC	Kebele groups			
	Pasture-cropland	Khat-Cropland	Woody vegetation	Accessible-wealthy
Arable land	-33.9	-45.7	-16.7	-24.6
Coffee plantation	14.7	20.0	12.3	20.1
Cultivated wetland	-0.5	-0.4	-0.2	-0.6
Eucalyptus Plantation	11.6	11.2	5.0	4.7
Farmland woody vegetation	-0.3	-0.4	-0.1	-0.2
Forest	-0.1	-0.1	-0.1	-0.8
Fruits and vegetables	0.0	0.0	0.0	0.0
Grazed wetland	0.0	0.0	0.0	0.0
Khat	13.7	11.9	2.4	2.5
Pasture	-5.5	3.1	-2.7	-3.8
Settlement	0.0	0.3	0.2	-0.6
Towns	0.3	0.0	0.0	3.3

Supplementary Table S7. LULC changes by kebele groups for Mining green gold scenario (in %).

	Kebele groups			
LULC	**Pasture-cropland**	**Khat-Cropland**	**Woody vegetation**	**Accessible-wealthy**
Arable land	-33.2	-22.0	-14.5	-23.4
Coffee plantation	50.6	40.6	60.8	72.1
Cultivated wetland	-0.3	-0.2	-0.1	-0.5
Eucalyptus Plantation	0.0	0.0	0.0	-0.2
Farmland woody vegetation	-2.1	-1.7	-0.7	-1.0
Forest	-7.8	-12.2	-41.2	-41.4
Fruits and vegetables	0.0	0.0	0.0	0.0
Grazed wetland	0.0	0.0	0.0	0.0
Khat	0.0	0.0	0.0	0.0
Pasture	-7.5	-4.7	-4.4	-8.3
Settlement	0.0	0.3	0.2	-0.6
Towns	0.3	0.0	0.0	3.3

Supplementary Table S8. LULC changes by kebele groups for Biosphere reserve scenario (in %).

	Kebele groups			
LULC	Pasture-cropland	Khat-Cropland	Woody vegetation	Accessible-wealthy
Arable land	-19.8	-29.0	-10.7	-18.4
Coffee plantation	0.0	0.0	0.0	-0.1
Cultivated wetland	-0.5	-0.4	-0.2	-0.6
Eucalyptus Plantation	0.0	0.0	0.0	-0.2
Farmland woody vegetation	14.4	13.3	6.3	10.6
Forest	0.0	0.0	0.0	-0.6
Fruits and vegetables	11.9	20.2	5.8	8.4
Grazed wetland	0.0	0.0	0.0	0.0
Khat	0.0	0.0	0.0	0.0
Pasture	-6.3	-4.3	-1.4	-2.0
Settlement	0.0	0.3	0.2	-0.5
Towns	0.3	0.0	0.0	3.3

Supplementary Table S9. LULC changes by kebele groups for Food first scenario (in %).

	Kebele groups			
LULC	**Pasture-cropland**	**Khat-Cropland**	**Woody vegetation**	**Accessible-wealthy**
Arable land	39.8	32.3	32.3	43.5
Coffee plantation	-0.2	-0.2	-0.5	-1.2
Cultivated wetland	-5.9	-5.9	-4.2	-4.4
Eucalyptus Plantation	-0.1	0.0	0.0	-0.2
Farmland woody vegetation	-3.8	-3.8	-0.9	-1.2
Forest	-23.7	-18.5	-23.3	-32.6
Fruits and vegetables	3.2	4.0	1.8	1.7
Grazed wetland	-1.1	-1.1	-0.2	0.0
Khat	-0.1	0.0	0.0	0.0
Pasture	-8.0	-7.0	-5.1	-8.3
Settlement	-0.5	0.3	0.2	-0.6
Towns	0.4	0.0	0.0	3.3

Supplementary Table S10. Narrative scenarios with key indicators.

	Scenarios			
Indicators/main crops	**Gain over grain**	**Mining green gold**	**Coffee and conservation**	**Food first**
Food crops (mainly maize, wheat, barely, teff, sorghum)	Remain in very limited space such as cultivated wetlands	Little food is produced on marginalized areas	Food crops are grown interspersed with pasture and tree plantations	Food crops expanded over the landscape mainly by large-scale farming
Local cash crops (mainly coffee, khat, fast-growing trees, mainly eucalyptus)	Farmers increase cash crops by reducing food crops	Not widespread, limited to unsuitable areas for large-scale coffee plantation	Traditional coffee remains in forest, coffee plantations are not favoured.	Coffee is not grown, other cash crops remain on steep slopes and hills
Large-scale coffee plantations	No large-scale coffee plantations	Landscape mainly consists of monocultured large-scale coffee plantation by investors	No large-scale coffee plantations, but traditional coffee remains in natural forests	No coffee plantations due to climate change
Livestock production and communal grazing	Pasture for livestock remains in very limited areas such as grazed wetlands	Pasture for livestock remains in very limited areas such as grazed wetlands	Pastures for livestock and communal grazing are well maintained	Remains on steep slopes
Woody vegetation	Mostly maintained, no clearing of woody vegetation	Woody vegetation conducive for coffee cultivation is converted to plantations by investors	Woody vegetation is maintained; landscape is diversified with mosaic of forest and farmland	Woody vegetation is cleared for cropland expansion

Chapter III

Chapter III

Spatial predictions for the distribution of woody plant species under different land-use scenarios in southwestern Ethiopia

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Abstract

Context

Deforestation, forest degradation and intensification of farming threaten terrestrial biodiversity. As these land-use changes accelerate in many landscapes, especially in the Global South, it is vital to anticipate how future changes might impact specific aspects of biodiversity.

Objectives

The objectives of this study were to model woody plant species richness in southwestern Ethiopia, for the present and for four plausible, spatially explicit scenarios of the future (‘Gain over grain’, ‘Mining green gold’, ‘Coffee and conservation’ and ‘Food first’).

Methods

We used cross-validated generalized linear models for both forest and farmland, to relate empirical data on total and forest-specialist woody plant species richness to indicators of human disturbance and environmental conditions. We projected these across current and future scenario landscapes.

Results

In both farmland and forest, richness peaked at intermediate elevations (except for total species richness in farmland) and decreased with distance to the forest edge (except for forest specialist richness in forest). Our results indicate that the ‘Mining green gold’ and ‘Food first’ scenarios would result in strong losses of biodiversity, whereas the ‘Gain over grain’ scenario largely maintained biodiversity relative to the baseline. Only the ‘Coffee and conservation’ scenario, which incorporates a new biosphere reserve, showed positive changes for biodiversity that are likely viable in the long term.

Conclusions

The creation of a biosphere reserve could maintain and improve woody plant richness in the focal region, by forming a cluster with existing reserves, would be a major step forward for sustainability in southwestern Ethiopia.

Keywords: Forest specialist richness, Land use scenarios, Southwestern Ethiopia, Spatial prediction, Total species richness, Woody plants

Introduction

Land-use change, including deforestation, forest degradation and intensification of farming, threatens terrestrial biodiversity (WWF 2020; Meyfroidt et al. 2022). Land use and land cover (LULC) change is projected to intensify, exacerbating pressure on biodiversity (Powers and Jetz 2019) and endemic species in particular (Kobayashi et al. 2019). It is therefore vital to anticipate what some plausible future land-use changes might look like and how they would impact specific aspects of biodiversity.

Biodiversity modelling based on scenarios of land-use change can be useful for understanding plausible future biodiversity loss (e.g., Leclère et al. 2020; Sala et al. 2000). However, most studies have modelled biodiversity impacts at global and regional scales, using climate and LULC data at coarse (e.g., 1 km) spatial resolution (but see Nelson et al. 2009). Such broad scale approaches are valuable but cannot capture local nuances, which limits their usefulness for local stakeholders and local conservation planning (Franklin 2010a). Here, we focus on developing fine-scale analysis to support local decision-making.

Analyzing land-use change at the landscape scale—that is, within fine-grain land cover mosaics ranging in extent from some square kilometers to hundreds of square kilometers (Fischer and Lindenmayer 2007)—can be particularly useful, because landscapes can be conceptualized as interlinked social-ecological systems (Wu 2013; Oteros-Rozas et al. 2015; Fischer et al. 2017). However, landscape-scale scenarios are often ‘narrative’ in nature, without explicitly modelled biodiversity outcomes. Better connecting landscape-scale narrative scenarios to specific biodiversity outcomes would be valuable to address potential trade-offs between alternative plausible futures.

In this paper, we modeled woody plant species diversity under four plausible future social-ecological scenarios in southwestern Ethiopia, a recognized biodiversity hotspot (Mittermmeier et al. 2011). The region supports moist evergreen Afromontane forests (Hylander et al. 2013) and is the origin of Arabica coffee *Coffea arabica* (Senbeta and Denich 2006). Woody plant species have important social and ecological functions in the region. They support many other species including globally significant populations of birds and mammals and thereby contribute significantly to local biodiversity (e.g., Gove et al. 2008; Hylander and Nemomissa 2008). They also contribute to multiple ecosystem services, such as house construction, farm implements, poles and timber, fuel wood, animal fodder, soil fertilization and honey production, that support the livelihoods of local people (e.g., Ango et al. 2014; Shumi et al. 2021).

In this study, we build on our earlier translations of four narrative land use scenarios into spatially explicit land use scenarios (Duguma et al. 2022). The scenarios are entitled *Gain over grain* (emphasis on cash crops such as coffee, khat and eucalyptus), *Mining green gold* (emphasis on coffee plantation), *Coffee and conservation* and *Food first* (emphasis on food crops) that are summarized in more detail in Sect. “Social-ecological scenarios and their implications for land use” below. Drawing on the corresponding land use maps of the present and the future, we used statistical models to relate empirical data on woody plant species richness to indicators of human disturbance and environmental conditions in order to make spatial predictions at the landscape level. Our goal was to spatially model total woody plant species richness (hereafter, total species richness) and forest specialist woody plant species richness (hereafter, forest specialist species richness), both for the present-day situation and for the four future land use scenarios. Our findings can help to raise awareness of the sensitivity of woody plant biodiversity to different social-ecological development pathways and can support ecologically informed decision-making within the study region. In particular, such spatially explicit biodiversity mapping can be reintegrated into further rounds of social-ecological scenario planning that consider the tradeoffs between ecological and socioeconomic outcomes.

Methods

Study area

The study area encompassed the forest and farmland mosaic of three administrative districts of Jimma zone of Oromia region in southwestern Ethiopia—namely, Gera, Gumay and Setema. Each district includes several smaller administrative units called “kebeles”, that are an important level of local management and decision-making (Fig. 1). Dominant woody plant species in the study area include *Croton macrostachyus*, *Vernonia auriculifera*, *Vepris dainellii*, *Bersama abyssinia*, *Galiniera saxifrage*, *Syzygium guineense*, *Pouteria adolfi-friederici*, *Chionanthus mildbraedii*, *Dracaena afromontana*, *Allophylus abyssinicus*, *Coffea arabica* and *Millettia ferruginea* (Shumi et al. 2018, 2019b). C. *arabica* is native to the region and naturally grows under the shade of trees in moist evergreen Afromontane forest. The study area is undulating and falls within elevations of approximately 1200 to 3000 m above sea level (supplementary Fig. S1). The landscape is dominated by smallholder farmers, whose main economic activities are cereal crop production, livestock rearing and coffee production. We divided the study area into farmland and forest (patches of woody vegetation ≥ 1 hectare; Fig. 1). Because we expected different social-ecological drivers to operate in these two very different environments, we modeled farmland and forests separately and then merged results to summarize for the whole landscape and by kebele.

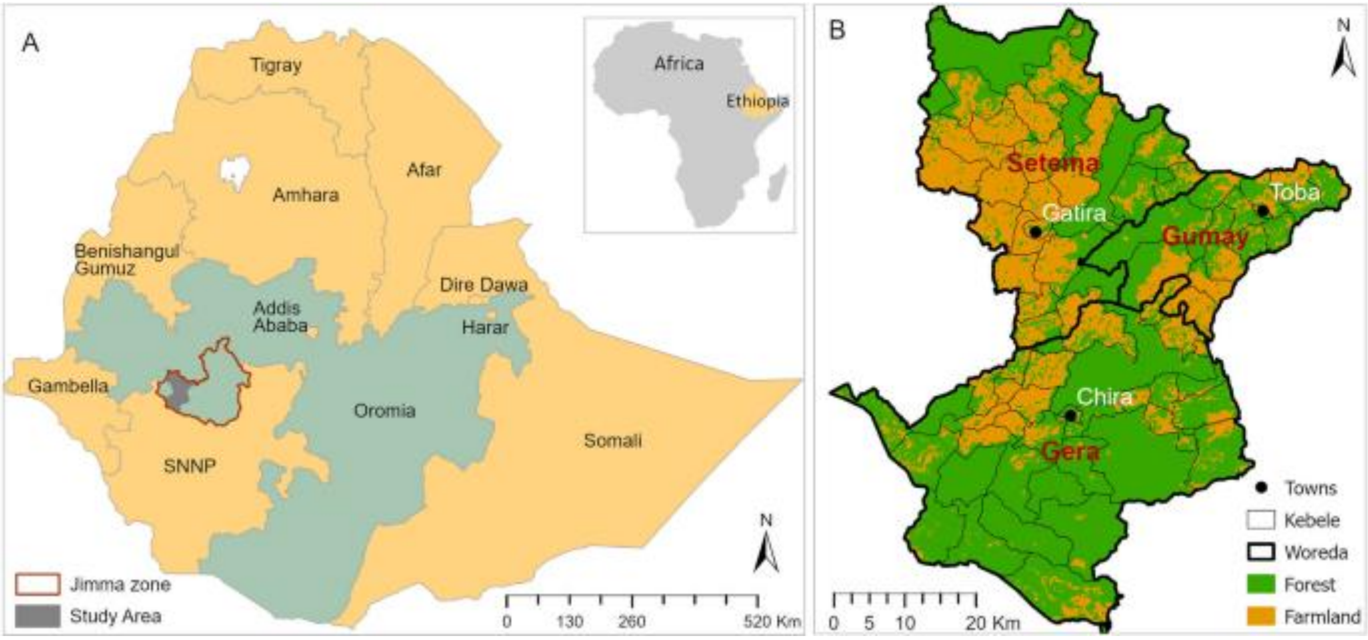

Fig. 1. A the study area in Jimma Zone, Oromia region (green grey) within Ethiopia (other regions are tan-colored); **B** the district boundaries (delimited by a thick black line and labelled in red) and lower administrative boundaries (kebeles; thin black lines) in the study area. The underlying land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

Social-ecological scenarios and their implications for land use

Four qualitative narrative scenarios (i.e., ‘Gain over grain’, ‘Mining green gold’, ‘Coffee and conservation’ and ‘Food first’) describing potential social-ecological conditions in 2040 were developed through participatory scenario planning (Jiren et al. 2020). These considered plausible environmental, social and economic changes and were translated into spatially explicit, quantitative land use maps (Fig. 2, supplementary Fig. S2A–E) (Duguma et al. 2022).

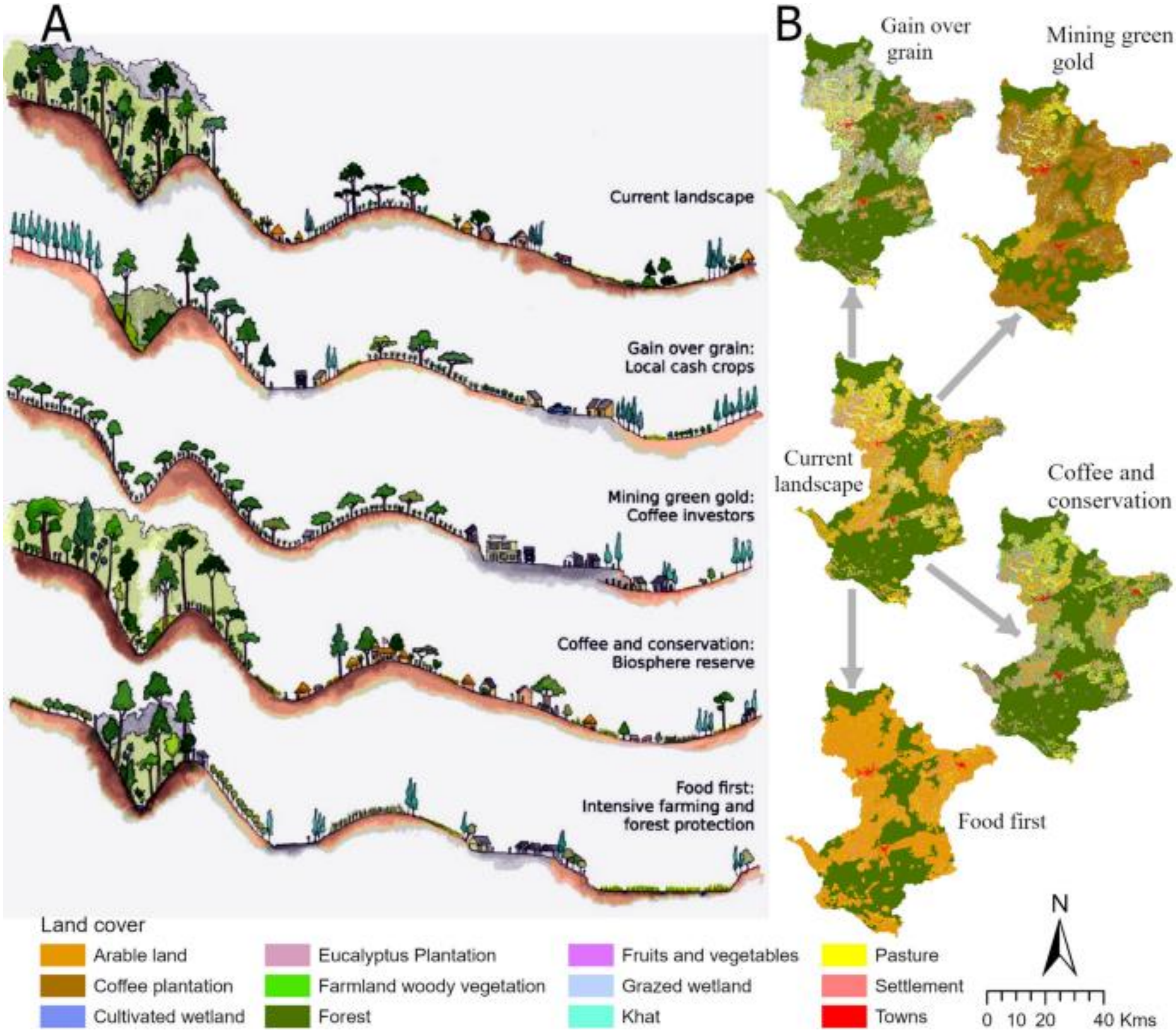

Fig.2. A A cross-sectional illustration of the present landscape and the four scenarios (reproduced from Jiren et al. 2020) and **B** spatially explicit, quantitative LULC maps of the current and the scenario landscapes (reproduced from Duguma et al. 2022). High resolution versions of the maps are provided in Fig. S2A-E

Briefly, the ‘Gain over grain’ scenario prioritizes farmers’ specialization and commercialization to boost development: traditional food cropping is abandoned in favor of cash crops such as coffee, the stimulant drug khat (*Catha edulis*) and fast-growing trees (e.g., *Eucalyptus*). The ‘Mining green gold’ scenario is characterized by the intensification of coffee production through large investors who use modernized, high-input production: farmland and forests conducive for coffee investment have been transferred to capital investors for the creation and expansion of coffee plantations. The ‘Coffee and conservation’ scenario is based on a more balanced land use approach: a diversified mosaic of forest and farmland consisting of a core zone with unused natural forest, a buffer zone for low-intensity production of local coffee, wild honey and other forest products and an outer zone with interspersed cropland, pastures and tree plantations. The ‘Food first’ scenario is characterized by the production of large amounts of cereal crops through intensive, large-scale agriculture, which involves extensive land consolidation, including the clearing of woody vegetation and expansion of cropland on flatlands and drained wetlands (Fig. 2).

Data

Woody plant diversity

Woody plant species of all ages (with a minimum height of 150 cm) were surveyed in 72 farmland sites (Shumi et al. 2018) and 108 forest sites (Shumi et al. 2019b). Sites were 20 m × 20 m quadrats, which were stratified across major landscape gradients. Species were classified into forest specialist, generalists and pioneer species. Here, we focused on two response variables: total species richness and forest specialist species richness.

Candidate predictors

We identified fifteen candidate predictors based on our ecological knowledge of the landscape, as well as data availability for the baseline and future scenarios. These included topographic variables and indicators of human disturbance. Coarse-scale climatic variables and latitude/longitude information were considered less important locally than topography and were therefore not included (Table 1, (see also Franklin 2010b)). Topographic variables were derived from the 30 m ASTER DEM (NASA/METI/AIST/Japan Spacesystems and U.S./Japan ASTER Science Team 2009). As measures of human disturbance, we included current and historical distance of sites from the forest edge, farmland type, forest type, percent woody vegetation at different scales (at 1 ha, 200 m, 500 m and 2 km) and land cover diversity (Table 1).

Table 1 Table 1. Variables used in the model building process. The land use maps used to derive some of the predictor variables were generated by (Duguma et al. 2022) and are highlighted by an asterisk (*).

Variables	**Source**	**Included in farmland models**	**Included in forest models**
Elevation	30 m ASTER DEM	Yes	Yes
Farmland type: historical farmland or new farmland	Derived from LULC map generated from Landsat (1985) and Sentinel (2019)*	Yes	No
Current farmland distance from the forest edge	Generated from LULC map*	Yes	No
Historical farmland distance from forest edge	Generated LULC map of 1985	Yes	No
Forest type: Primary (pre-1985) or secondary forest (newly occurring since 1985)	Derived LULC map generated from Landsat (1985) and Sentinel (2019)*	No	Yes
Current forest distance from the forest edge	Generated from LULC map*	No	Yes
Heat load index	Derived from ASTER DEM (Olsson et al. 2009)	Yes	Yes
Percent woody vegetation within a 1 ha (56 m radius) moving window	Generated from LULC map*	No	No
Percent woody vegetation within a 500 m radius moving window	Generated from LULC map*	No	No
Percent woody vegetation within a 2 km radius moving window	Generated from LULC map*	Yes	Yes
Land cover diversity within 1 ha	Generated from LULC map*, using Simpson’s diversity index of land covers in Fragstats 4.2 (McGarigal and Ene 2015).	Yes	No
Land cover diversity within a 200 m radius	Generated from LULC map*, using Fragstats 4.2 Simpson’s diversity index of land covers (McGarigal and Ene 2015).	Yes	No
Slope in degrees	Derived from ASTER DEM	Yes	Yes
Topographic wetness index	Derived from ASTER DEM using ArcGIS	Yes	Yes

Variable preprocessing is detailed in the supplementary (S1) and summarized here. We examined predictor variables using histograms and transformed if this improved normality. We removed strong co-linear variables. We included quadratic terms if these were indicated by theory and supported by the data. We removed variables that were deemed unreliable (due to remaining skew resulting in poorly supported and unexpected bivariate relationships).

Model selection

We developed four models for woody plant species across farmland and forest areas (two in each environment), using total species or forest specialist species richness as outcome variables. As our aim was to produce spatial predictions, our model selection process focused on finding models that would both fit the data well and perform well in the prediction processes. We used generalized linear modeling due to the interpretability of these models with respect to the predictor variables. The model evaluation and cross-validation process is detailed in the supplementary material (S1) and summarized here. To be able to test the predictive power of the models and avoid overfitting, we first split the data into training and testing sets based on key environmental PCA dimensions (S1). Models were fit and selected on the training set and evaluated in terms of root mean square error (RMSE) of the (1) training set predictions, (2) test set predictions, (3) k-fold cross-validation across the whole dataset, with sevenfold based on environmental strata and (4) k-fold cross-validation across the whole dataset, with 10 random folds. We conducted modelling in R v 4.1.2 (R Core Team 2019), including the packages identified below.

The model selection process (detailed in S1 and summarized here) started by selecting the appropriate regression family. We first fit a Poisson GLM (log link) to the full models and modified this to a negative binomial (R package: MASS; Venables and Ripley 2002) where overdispersion was indicated (i.e., for the total species richness models in forest and farmland). For the model of total woody species richness in farmland we fit truncated (> 0) Poisson and negative binomial GLMs (log link; R package: glmmTMB; (Brooks et al. 2017)), as the sampling only took place in plots where woody vegetation was present (i.e., the data had no zero values). We then reduced these full models by identifying the top subsets of each of these that performed well either in terms of AICc or mean RMSE from the random-strata cross-validation (identified with the R package MuMIn; Barton 2020). We selected 5–10 models per task which showed high accuracy and indicated a good model fit (R package DHARMa; Hartig 2021). We re-fit these on the whole sample data and repeated the examination of the models and model residuals. Where these indicated poor fits, we repeated the selection process with modified or additional variables, including interaction terms. If spatial autocorrelation was indicated, we accounted for this by including the spatial covariance matrix as an exponential spatial random effect (R package: glmmTMB; Brooks et al. 2017).

Final models were then chosen based on the spatial predictions conforming with theoretical expectations and expert opinion across all scenarios. We projected out selected models (2–3 per modelling task) to the study region, including for the current landscape and future scenarios. Models with spatial components were projected without known random (spatial) effects to better reflect underlying patterns driven by the predictors. To ensure that our models were not extrapolated into substantially novel parameter spaces, we constrained the input raster predictor variables to a floor and ceiling observed in our field-based data. This constraint produced predictions consistent with current observed parameter ranges for most models. We further constrained the maximum value output for the model on total species richness in forest, as the prediction ranged substantially higher in a small subset of cells for this model, due to novel parameter combinations. We checked models for logical consistency, specifically that total species richness > forest specialist species richness scores for both the forest and farmland.

As our models did not explicitly distinguish coffee plantations from other types of forest cover—because intensive plantations are currently rare in the landscape—in the ‘Mining green gold’ scenario we applied a ceiling of four total species and two forest specialist species in plantation areas, based on highest values of species richness in the forest plots sampled that most closely resembled intensified coffee plantations.

Spatial predictions and model summaries at landscape and kebele level

The main purpose of the modelling was to produce spatial predictions of woody plants species richness for the current landscape as a baseline and the four scenarios. In each case, the results for farmland and forest were merged to produce a single predicted map for the entire study area (i.e. the landscape). Finally, we summarized our results at the kebele level to support local decision-makers using ArcGIS 10.6.1. Specifically, we subtracted the mean predicted values in each kebele for each scenario from the mean predicted values of the current landscape to obtain average changes in species richness at kebele level.

Results

Selected models

In farmland, total species richness increased with a decrease in historical distance to the forest edge, with an increase in land cover diversity and with an increase in slope; and decreased with topographic wetness index (Table 2). Forest specialist richness peaked at intermediate elevation, while it decreased with both current and historical distance from the forest edge and increased with greater land cover diversity (Table 2).

Table 2. Modeling results for the farmland for total and for forest specialist richness of woody plants. Highlighted are the terms included in the selected model, their coefficients, standard errors, p-values and percent variance explained. Both models had no significant spatial autocorrelation (p-value of Moran's I > 0.05).

Total species richness – model: glmmTMB (truncated >0, negative binomial distribution, link = log)				
Terms	Coefficients	Standard error	p-value	Percent variance explained
(Intercept)	2.6645	1.0939	0.0149	13.7
Historical distance	-0.0141	0.0077	0.0650	
Land cover diversity (1ha)	0.8333	0.3877	0.0316	
Slope	0.0991	0.1106	0.3699	
Topographic wetness index	-0.7951	0.4445	0.0736	
Forest specialist species richness – model: glm, Poisson, link = log				
(Intercept)	0.5360	0.8741	0.5397	19.3
Elevation	5.4554	1.6768	0.0011	
Elevation in quadratic term	-1.8200	1.5614	0.2438	
Historical distance	-0.0139	0.0140	0.3191	
Current distance	-0.1722	0.1604	0.2829	
Land cover diversity (1ha)	0.6979	0.5925	0.2389	

Total species richness increased in primary forest and decreased with distance from the forest edge. In addition, total species richness peaked at intermediate levels of both elevation and percent woody vegetation cover (Table 3). Forest specialist richness in forest showed similar relationships with forest type, elevation and percent woody vegetation cover. Even though current distance was not included in the selected model for forest specialist, forest specialist richness did appear to increase with increasing distance from forest edge (Fig. 3).

Table 3. Modeling results for the forest for total and for forest specialist richness of woody plants. Highlighted are the terms included in the selected model, their coefficients, standard errors, p-values and percent variance explained. Both models contained a spatial autocorrelation.

Total species richness – model: glmmTMB (negative binomial distribution, link = log, **spatial covariance matrix as an exponential spatial random effect**)				
Terms	Coefficients	Standard error	p-value	Percent variance explained
(Intercept)	2.7327	0.1201	< 2e-16	24.14
Forest type	0.2991	0.1170	0.0106	
Current distance	-0.0066	0.0053	0.2142	
Elevation	-0.5563	0.4214	0.1869	
Elevation in quadratic term	-0.6353	0.4025	0.1145	
Percent woody vegetation (in 2km moving window)	1.4326	0.4822	0.0030	
Percent woody vegetation (in 2km moving window) in quadratic term	-0.4131	0.3948	0.2954	
Forest specialist species richness – model: glmmTMB (negative binomial distribution, link = log, **spatial covariance matrix as an exponential spatial random effect**)				
(Intercept)	1.6353	12.2610	< 2e-16	48
Forest type	0.8560	5.8000	0.0000	
Elevation	0.2715	0.6610	0.5084	
Elevation in quadratic term	-1.1713	-3.0550	0.0023	
Percent woody vegetation (in 2km moving window)	1.3632	2.6400	0.0083	
Percent woody vegetation (in 2km moving window) in quadratic term	-0.5057	-1.1330	0.2573	

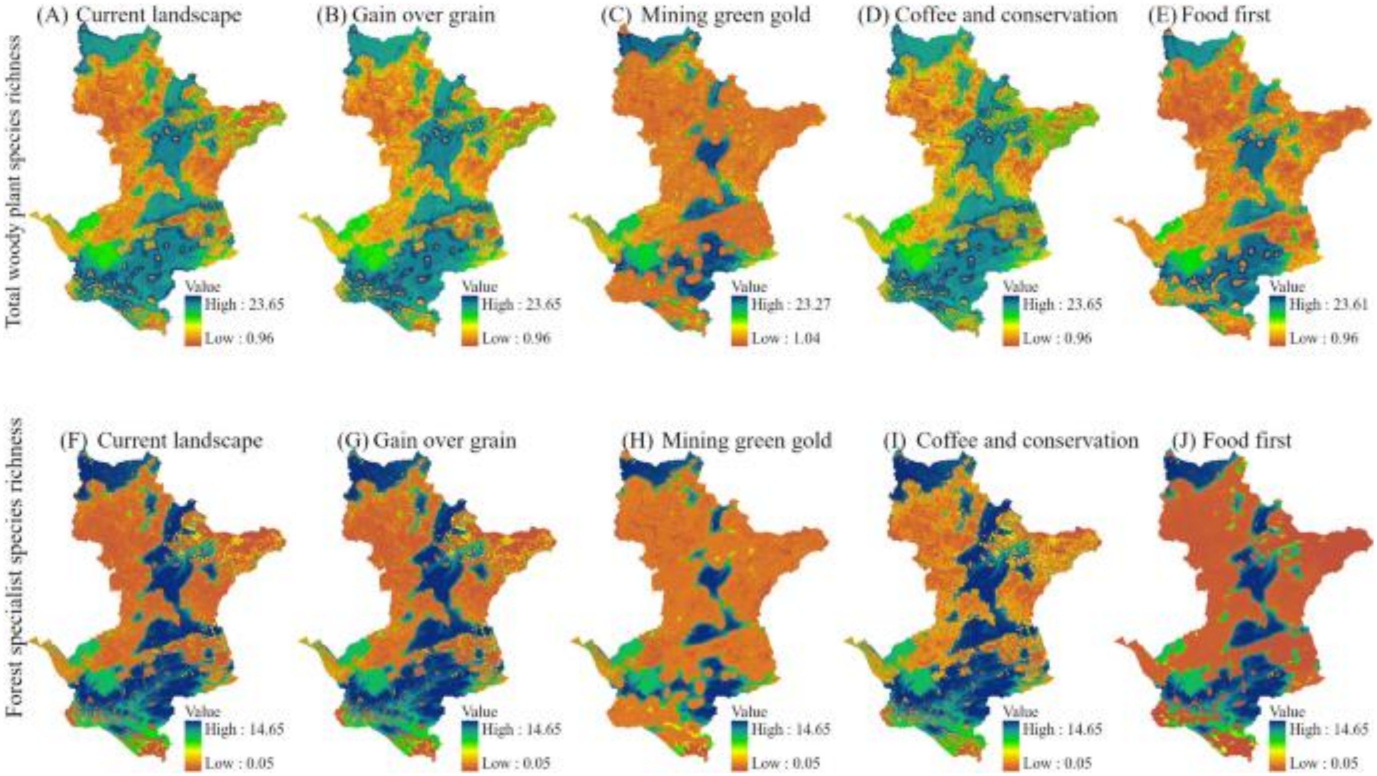

Fig. 3. Spatial predictions under the baseline and future scenarios for total species richness (upper panels, **A**–**E**) and forest specialist species richness (lower panels, **F**–**J**)

Spatial predictions across the landscape

Higher total species richness was found in forest compared to farmland, with scenarios differing largely due to the distinct distribution of woody vegetation in these main two habitats (Fig. 3). Under the ‘Gain over grain’, ‘Coffee and conservation’ and ‘Food first’ scenarios the distribution curves showed two peaks of total species richness near five and 19, depicting their relative distribution in farmland and forest, respectively (Fig. 4). However, while the ‘Gain over grain’ and ‘Coffee and conservation’ scenarios saw a slight general increase in species richness compared to the current baseline, the ‘Food first’ scenario experienced a general decline in species richness (Fig. 4). Under ‘Mining green gold’ where large parts of the forest were lost, the distribution curve for total species richness was concentrated around four.

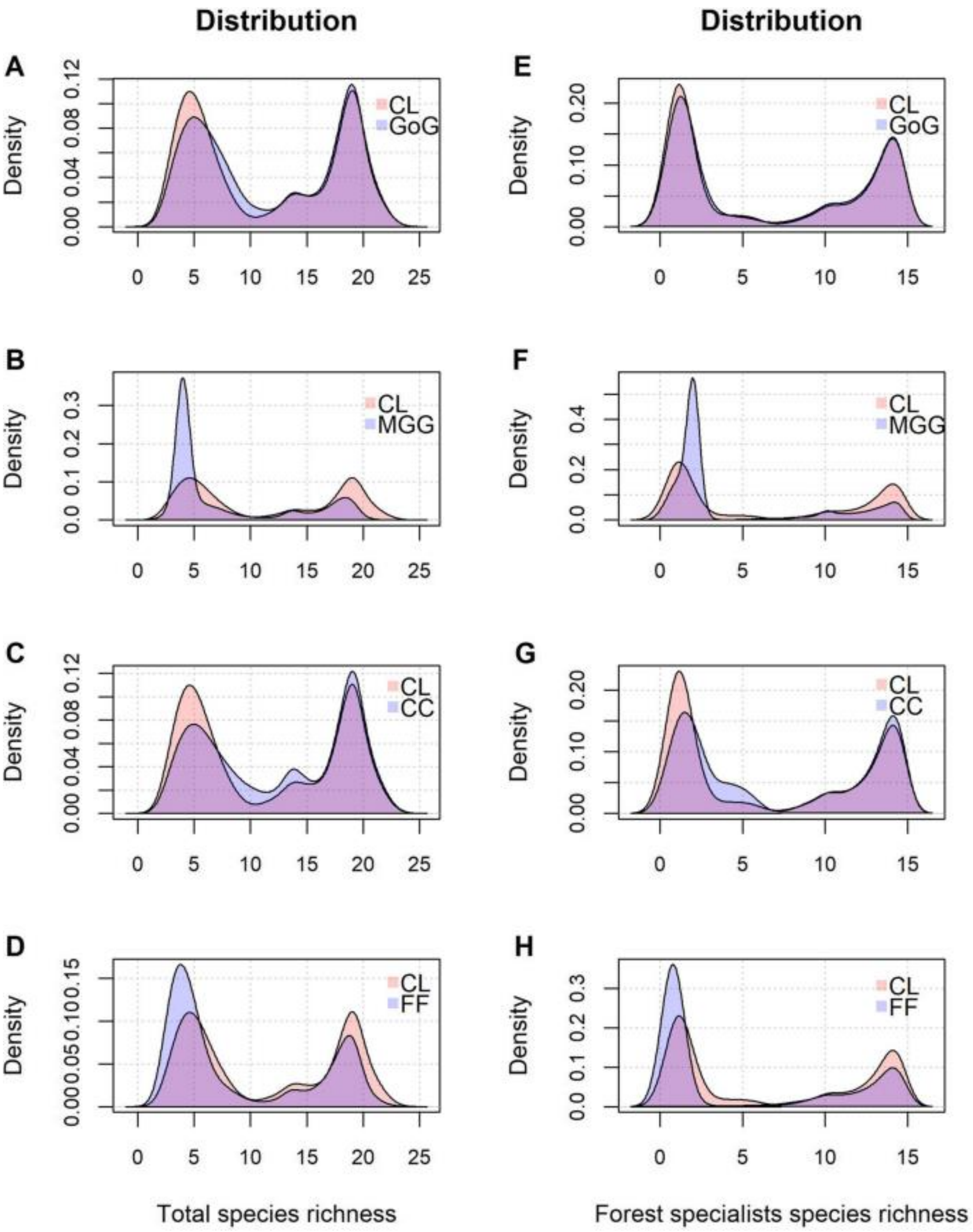

Fig. 4. Density distributions showing changes in woody plants species richness under the scenarios (*GoG* 'Gain over grain', *MGG* 'Mining green gold', *CC* 'Coffee and conservation', *FF* 'Food first') against the current landscape (CL). The left panels **A**–**D** illustrate changes in total species richness, while the right panels **E**–**H** present changes in forest specialist species richness.

Patterns for forest specialist were similar to total richness. Forest specialist richness was lower than total species richness overall, and forest specialist diversity was higher in forest than in farmland, especially towards the interior of the forest (Fig. 3). Peaks in their distributions were around one in farmland and 14 in forest (Fig. 4).

Changes in woody plant species richness at the kebele level

For total species richness, most kebeles showed little to no change in the ‘Gain over grain’ scenario, relative to the baseline, with only two kebeles (corresponding to two district towns) showing a loss in total species richness (Fig. 5). Both the ‘Mining green gold’ and ‘Food first’ scenarios showed losses in total species richness across a majority of kebeles. Changes were more heterogeneous for ‘Mining green gold’ compared to the more uniform responses under other scenarios, but also included the strongest losses where some kebeles lost up to 14 species of 18 total species. In the ‘Food first’ scenario, most kebeles lost one to four species of woody plants. In contrast, no kebele experienced losses in woody species richness in the ‘Coffee and conservation’ and more kebeles increased in species richness under this than in any other scenario (Fig. 5). Broadly speaking, similar patterns were found for forest specialist species (Fig. 5).

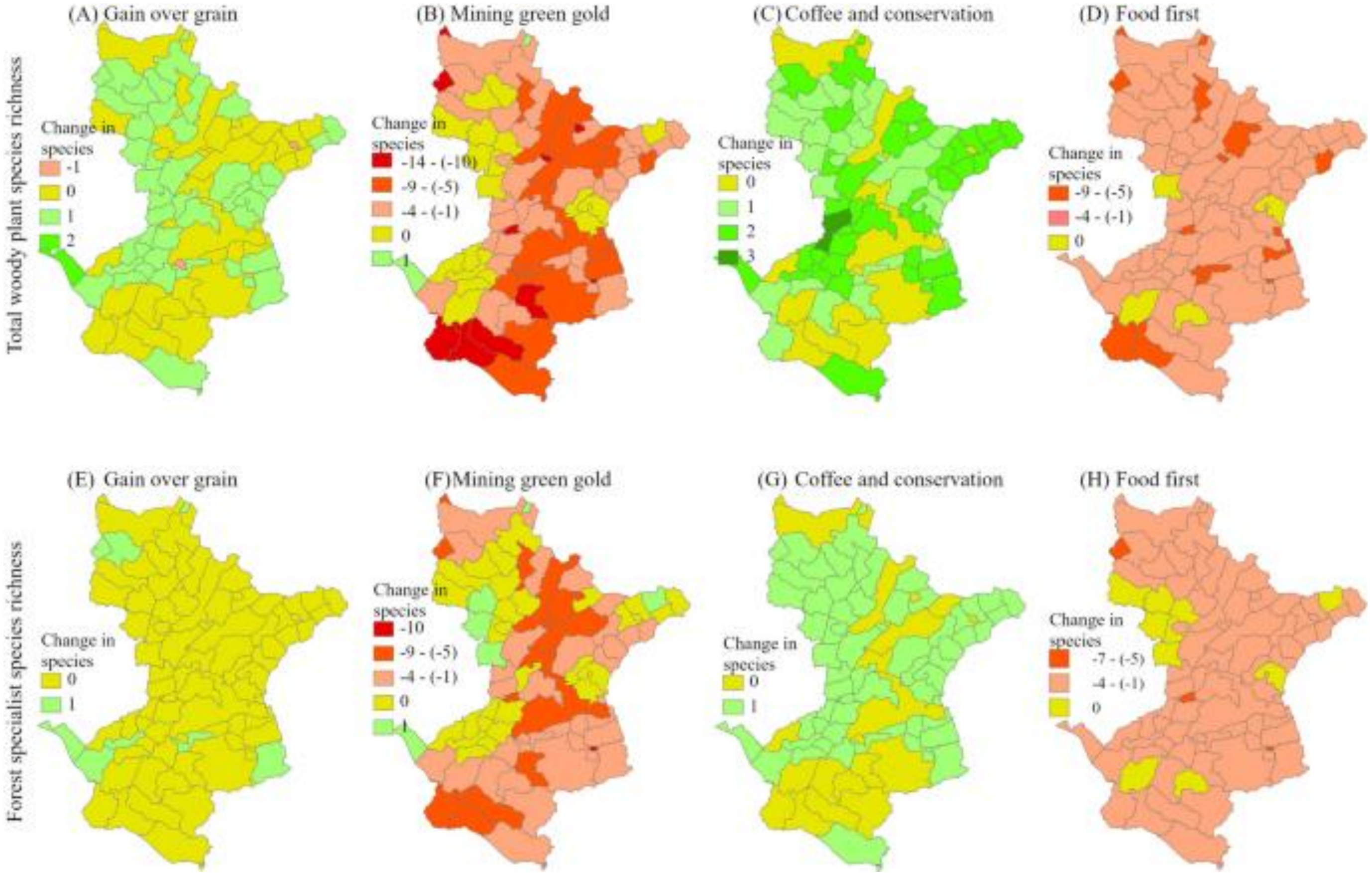

Fig. 5. Changes in mean species richness at the kebele level. The mean changes for each scenario were calculated against the current landscape as a reference point. The upper panels **A**–**D** show total species richness, while the lower panels **E**–**H** depict forest specialist richness

Discussion

Models of biodiversity at the landscape scale are powerful tools for natural resource management (Mateo et al. 2018). Here, we combined landscape-scale biodiversity models, including locally important variables that influence biodiversity, with future land use maps generated from participatory scenario planning to spatially predict plausible future changes in woody plant diversity. Our approach revealed clear differences in biodiversity responses among the scenarios. Biodiversity declined strongly in two scenarios, the ‘Mining green gold’ and ‘Food first’ scenarios. Slightly positive responses were observed for the ‘Gain over grain’ scenario, while richness was most positively affected in the ‘Coffee and conservation’ scenario. Below, for each scenario, we provide a more detailed discussion of possible trends at the landscape and the kebele levels, before considering general implications for conservation.

‘Gain over grain’

At the landscape scale, richness values changed only slightly from the current baseline in this scenario. In farmland, slight increases resulted from degraded farmland on steep slopes being covered by eucalyptus plantations (Duguma et al. 2022). Forest specialist richness showed no change mainly because it was associated with primary forest cover (Shumi et al. 2018), which remained unchanged in this scenario. At the kebele scale, most kebeles showed low to moderate changes in woody plant richness. Only two kebeles, namely those that were assumed to experience a strong future growth in human settlements (Duguma et al. 2022) lost species under this scenario.

Notably, smallholder-driven land use intensification as simulated in this scenario could have a positive impact on income and employment in rural households (Appelt et al. 2022). However, although our models showed slightly positive effects on biodiversity in the short term (20 years), in the long-term, especially the expansion of eucalyptus plantations may negatively impact biodiversity and thus ultimately also may be negative for local ecosystem services and human wellbeing (Rasmussen et al. 2018; Beckmann et al. 2019). Furthermore, our analysis focused on biodiversity impacts that follow spatial changes in land use and cover. An increased use of agrochemicals under the ‘Gain over grain’ scenario, which is already common practice in more intensified cash crop landscapes elsewhere in Ethiopia (e.g., Gessesse Dessie 2013; Cochrane and O’Regan 2016), may contribute to future negative impacts on biodiversity that our current analysis was not able to capture.

‘Mining green gold’

This scenario showed strong losses in total and forest specialist species richness compared to other scenarios, because this scenario was mainly driven by the clearance of small patches of woody vegetation in farmland within future coffee elevation and by conversion of forest to large scale coffee plantation. Our results are consistent with evidence of a rapid decline in woody plant biodiversity with increasing yields in coffee agroforests, especially under intensive management (Geeraert et al. 2019; Zewdie et al. 2022). Similarly, investments intended for the production of export-oriented commodities often result in strong biodiversity losses in tropical forest (Davis et al. 2020).

Notwithstanding the overall negative effects of this scenario on biodiversity, effects among kebeles were more heterogeneous compared with other scenarios. High and low elevation kebeles (which were mainly outside the elevation range suitable for coffee) that were dominated by arable land and with little woody vegetation showed no change in both total and forest specialist species richness. Other kebeles showed particularly strong losses in species richness (up to 14 total species and 10 forest specialist species; Table S1); these kebeles had high proportions of woody vegetation (from 73 to 95%) and were located at intermediate elevations, that are most suitable for growing coffee (Hylander et al. 2013; Moat et al. 2017). Future differences in land use and landscape suitability for specific crops thus drove diverging responses in this scenario.

‘Coffee and conservation’

Positive outcomes for the diversity of woody vegetation were observed for this scenario, which was largely based on the concept of sustainable land management (Jiren et al. 2020). The resulting heterogeneous landscape allowed for an increase in both total and forest specialist species richness in previously homogeneous farmland areas. Indeed, this scenario reflected key characteristics for biodiversity-friendly farming such as the maintenance of native vegetation, the improvement of heterogeneity and structural complexity and an avoidance of the use of agrochemicals (Perfecto and Vandermeer 2010; Fischer et al. 2013). Moreover, the scenario would help to protect the gene pool of wild Arabica coffee through conservation of the last remaining coffee forests, which is considered a high conservation priority (Aerts et al. 2015). The positive effects on woody vegetation at the landscape level resulted in relatively consistent, positive outcomes at the kebele level (Fig. 5). Our results thus suggest that the establishment of a new biosphere reserve, or similar approach that would result in a sustainably managed, diversified landscape, could make major contributions to biodiversity conservation in the region. Especially if published guidelines for the establishment and management of biosphere reserves are followed (Stoll-Kleemann and Welp 2008; Van Cuong et al. 2017), it is highly plausible that the ‘Coffee and conservation’ scenario would indeed contribute to the urgently required conservation of Ethiopian coffee forest. The creation of a new biosphere reserve would lead to a spatially connected cluster of several biosphere reserves within southwestern Ethiopia (Urban and Beswick 2018)—that together, would generate a currently unreached level of regional connectivity for the moist Afromontane forest biome.

‘Food first’

This scenario was associated with major losses in total and forest specialist species at both the landscape and kebele levels, largely due to decreased farmland heterogeneity and significant deforestation in the wake of large-scale agricultural land expansion and intensification. Especially forest specialist declined in response to agricultural expansion and intensification that homogenized the landscape (Fig. 4). This scenario would represent a continuation of current trends of forest change in our study region, where deforestation has increased since 1973, especially in areas not suitable for growing (forest) coffee (Hylander et al. 2013). While forest loss already is widely acknowledged as a primary driver of biodiversity loss (Le Roux et al. 2019; Caro et al. 2022), our results further support the important role of forests for future biodiversity conservation. Beside its effect on biodiversity loss, several studies in Ethiopia and Rwanda have also revealed negative social-ecological impacts of large-scale intensive farming on smallholder farmers, including losses in the quantity and diversity of food and income, as well as reductions in forest-based ecosystem services (e.g., Moreda 2017; Kim et al. 2022).

General conservation implications

For forest specialist, which have a high conservation priority (Shumi et al. 2019b, a), differences between primary and secondary forests and percent woody vegetation cover were the main driving factors in forest, whereas current and historical distance from the forest edge and land cover diversity were the main driving factors in farmland. Our results also indicate that woody species in general are sensitive to local differences and changes in future landscapes within our study area. Two scenarios, ‘Mining green gold’ and ‘Food first’, resulted in relatively strong losses of biodiversity, while two other scenarios, ‘Gain over grain’ and ‘Coffee and conservation’, resulted in slight and relatively strong gains in biodiversity, respectively.

The ‘Mining green gold’ and ‘Food first’ scenarios are relatively well-aligned with Ethiopia’s current large-scale land investment policy that intends to improve food security, earn foreign currency, generate income from land rent fees and create employment (Rahmato 2011; Shete and Rutten 2015). However, existing government policy that favors agricultural intensification through highly hierarchical biodiversity and food security governance (Jiren et al. 2018) largely ignores the critical importance of woody plant species diversity and associated ecosystem services for local communities (e.g., Kassa et al. 2016). Future regional development strategies and land use policies therefore need to more fully recognize the needs and practices of local communities with respect to managing woody vegetation.

Furthermore, especially in highly forested areas, large-scale agricultural intensification for monoculture crops typically leads to losses of biodiversity and ultimately has negative impacts on many important ecosystem services and ultimately also on human well-being (Rasmussen et al. 2018). Thus, these two scenarios are unlikely to be sustainable, or at the very least would necessitate exceptionally proactive measures to avoid losses in biodiversity and important ecosystem services (Tadesse et al. 2014; Shumi et al. 2021). While the ‘Gain over grain’ scenario indicates slightly positive biodiversity responses, this scenario involved land use and management changes that could negatively affect biodiversity in the long run and which are not captured by our spatial analysis. Proactive management thus would also be needed under this scenario to avoid unsustainable outcomes.

The ‘Coffee and conservation’ scenario showed the most clearly positive changes for biodiversity and also could result in longer-term sustainable outcomes. In addition to conservation benefits, the scenario may lead to positive socioeconomic outcomes for smallholder households, who closely depend on the ecosystem services generated from the landscape (Tadesse et al. 2014; Ango 2018; Shumi et al. 2021). While the short-term socioeconomic gains may be more moderate compared to the benefits that a limited group of households may experience under the ‘Gain over grain’ scenario, whatever gains there are would possibly be distributed more equitably across the study region and among households. Our work thus supports the idea of “working lands conservation” (Kremen and Merenlender 2018) being able to support both biodiversity and goods and services for humanity, while maintaining the abiotic conditions necessary for long-term sustainability and resilience. The creation of an additional biosphere reserve, to form a cluster with existing other reserves, could therefore represent a sustainable trajectory for southwestern Ethiopia.

Future research and limitations

We have shown in our research how spatially explicit land use and land cover scenarios that were co-generated with stakeholders, can be used to map and predict woody plant biodiversity under different social-ecological conditions. We acknowledge that there are limitations to our approach—for example it can be challenging to translate narrative scenarios into spatially explicit maps (e.g., Duguma et al. 2022) and maps cannot fully capture all aspects of social change that may take place in the future. Moreover, a realistic outcome for the study area may well be a combination of aspects of all different scenarios, or different aspects of the scenarios may manifest in different parts of the landscape. Future research should further explore these questions, for example by working with stakeholders to identify which aspects of different scenarios are most desirable in different sections of the study area.

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Supplementary materials

Supplementary material **S1** of this chapter contains details of the method section of this chapter that includes libraries and file descriptions, stratification variables, data examination and transformation, and model selection process. It is available online:

https://link.springer.com/article/10.1007/s10980-023-01614-0#Sec21.

Table S1. Characteristics of kebeles by their Altitude (in meters) and proportion of land cover types (in %).

UID	Kebele Name	Minimum Altitude	Maximum Altitude	Mean Altitude	Arable land	Cultivated wetland	Grazed wetland	Pasture	Settlement	Woody Vegetation
GK1	Bore Dedo	2134	2587	2327.9	61.5	9.8	0.8	11.3	0.6	16
GK2	Bore Gogo Boricho	2098	2510	2240.6	51.9	14.3	0.3	17.5	0	16
GK3	Deka	1511	2296	1759	12.6	4.3	0	6.7	0.8	75.6
GK4	Chira Town	1957	2113	2045.8	13.8	3.5	0	4.6	36.6	41.6
GK5	Duseta	2099	2444	2300.6	62.9	8.8	2.4	9.4	2.6	14
GK6	Gebakoro	2271	2582	2396.2	45.3	3	0	12	0.8	38.9
GK7	Gedagute Gemina	1819	2934	2540.9	36.4	2.9	0	9.2	0.4	51.2
GK8	Dacho	1487	2723	1850.6	2.2	0.8	0	0.9	1	95
GK9	Geniji Chala	1866	2098	1978.1	18.1	8.4	0	11.7	6.9	55
GK10	Gere Ifalo	1415	2462	1906.7	3.3	0.3	0	0.9	0.3	95.2
GK11	Gina Chola	2180	2553	2349.9	61	9.2	0	7.3	12.4	10
GK12	Gurariso	1769	2299	1963.8	8.1	3	0	2.9	1.5	84.5
GK13	Gure Dako Kecha	1934	2390	2118.1	27.2	7.5	0	6.1	3.8	55.4
GK14	Anideracha	1848	2010	1899.2	24.3	11.3	0.4	32.6	4.5	26.9
GK15	Kele	1620	2904	2275	10.9	1.9	0	1.7	0.7	84.7
GK16	Kesebeday Kola	2142	2436	2303.6	57.4	5.6	0.1	9.5	3	24.5
GK17	Kinibibit	1864	2846	2209.3	29.7	5.7	0	15.8	0.6	48.2
GK18	Kola Suja	1849	2108	1912.4	28.6	15.3	0	31.6	0.6	23.9
GK19	Komibolicha	2298	2963	2642.9	60.3	5	0	6.5	1	27.2
GK20	Kubo Silech	1895	2522	2187	39	15.7	0.6	23.2	0.2	21.3
GK22	Muje	2167	2442	2301	61.5	11.1	0.9	10.7	1	14.7
GK23	Oba Toli	1458	2870	1813	4.9	2.5	0	4.6	1	87.1
GK24	Secha	2219	2804	2578.6	62.9	7.4	0	5.6	2.7	21.5
GK25	Sed Loya	1868	2601	2036.3	26.5	4.9	0	12.5	5.5	50.6
GK26	Tinibachale	2295	2719	2462.4	61.1	4.4	0.3	8.9	0.3	25.1
GK27	Tuma Teso	1853	2124	1932.7	21.8	8.7	0.5	19.9	1.2	47.9
GK28	Wala Wanija	1281	2025	1537.7	23	4.4	0	10.9	0.3	61.4
GK29	Kerisa	1862	2108	1918.5	26.4	9.1	0	21.5	7.8	35.1

GK30	Wegecha	2302	2504	2408.7	58.5	5	0.9	12.3	7.9	15.4
GuK1	Awisa Bilo	1440	1726	1597.1	27.2	16.7	0	7.8	0.9	47.4
GuK2	Bara Enchni	1938	2510	2268.8	65.8	11.1	0	4.4	0.1	18.5
GuK3	Berarigo	1779	2397	2149.9	28.6	8.3	0	8.9	0	54.2
GuK4	Bereguda	1396	1766	1565.9	25.6	19.8	0	5.2	3.4	46
GuK5	Berwerenigo	2125	2598	2267.8	69.4	12.3	1	11.1	0	6.1
GuK6	Chanido	1863	2449	2206.6	58.7	8.6	0	7.4	2	23.4
GuK7	Efyacgi	1510	1836	1696.3	23.3	6.2	0	9.7	7.2	53.5
GuK8	Gatokure	1764	2320	1987.7	21.9	4.4	0	8.5	5.3	60
GuK9	Guribodage	1446	1922	1660.5	48.3	20.1	0	10.6	1.1	20
GuK10	Kuda Kefi	1596	2213	1820	30.6	6.5	0	10.1	10.4	42.5
GuK11	Kudakunacho	1746	2313	1969.9	43.7	3.5	0	7.8	5.3	39.7
GuK12	Lima Tao	1473	1984	1678.2	33.6	7.6	0	14.5	3.4	40.9
GuK13	Nego Agu	1463	1993	1732.7	24.1	11.2	0	13.5	4.1	47.1
GuK14	Toba Town	1602	1878	1701	12.4	2.8	0	4.9	53.5	26.4
GuK15	Yasera Pera	1560	2276	1925.6	9.5	2.5	0	4	0.8	83.2
SK4	Chefeta Yera	2097	2275	2204.3	45.2	22.1	9.5	16.7	2.5	4
SK5	Demu Kufi	2195	2358	2281.9	35.1	13.4	2	39.3	0	10.2
SK6	Difo Mani	1517	2014	1751.6	31.6	8.7	0	22.8	3.5	33.4
SK7	Done	2132	2361	2211.6	41.4	10.4	5.6	30.7	0.3	11.5
SK8	Dora Ongo	2088	2334	2192.1	59.4	9.4	0	8.9	0.4	22
SK9	Doradocha	2031	2279	2161.1	48.6	11.9	0	17.3	4.1	18.2
SK11	Gatira Town	2102	2369	2240.1	43.8	6.5	0	6.3	29.9	13.5
SK12	Gela	1995	2275	2170.9	61.7	11	0.6	17.7	3.9	5
SK13	Gesecha	2163	2334	2238.9	42	11	4.6	29.8	1.1	11.5
SK14	Gido Bere	1777	2232	2045.6	43.7	11.1	0	9.7	0.2	35.2
SK16	Kuba Toba	2022	2212	2111.7	46.4	16	5.7	17.7	0	14.3
SK17	Masano	2151	2324	2224.4	49.6	12	8.7	22.8	0	6.9
SK18	Sata Gona	2206	2410	2321	28.1	11.9	0.3	24.8	0.1	34.9
SK21	Sedu	2150	2294	2224.9	54.7	11.5	4.1	23.1	2.9	3.6
SK22	Seta	1987	2281	2168.2	70.9	15.4	0	8.7	0	5.1
SK23	Setema Kecha	1628	2247	1947.6	17.5	3.4	0	10.3	0.7	68
SK25	Sheni Chemere	1602	2188	1974.9	25	10.5	0.2	13	0.7	50.7
SK26	Shoni Belira	1980	2267	2138.5	64.2	12.1	0.1	12.1	7.9	3.5
SK27	Sika	1678	2338	2196.7	19.3	6.5	1.2	14.8	0	58.2
SK29	Sogesecha (Kimisso)	2127	2291	2217.9	45	14.1	9.8	23.4	0.4	7.3
SK30	Solako	2139	2337	2217.2	33	14.7	1.4	36.3	0	14.5
SK31	Susatela	2158	2331	2219.2	46.4	11.9	4.8	27.5	5.4	4.1

Fig. S1. Main topographic features of the study area (A) Elevation in meters, (B) Slope in degrees, and (C) Aspect.

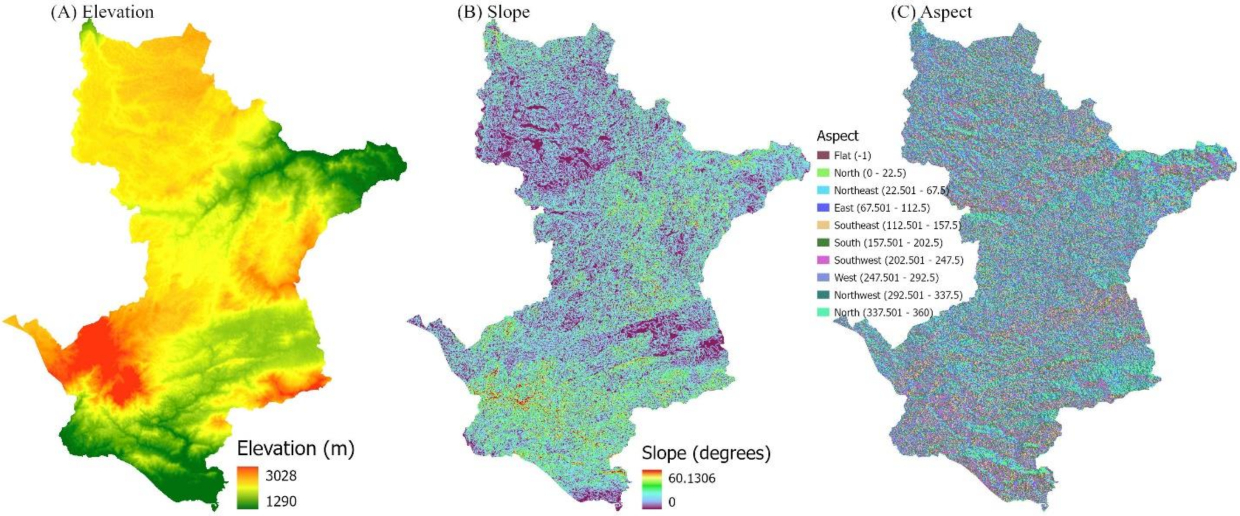
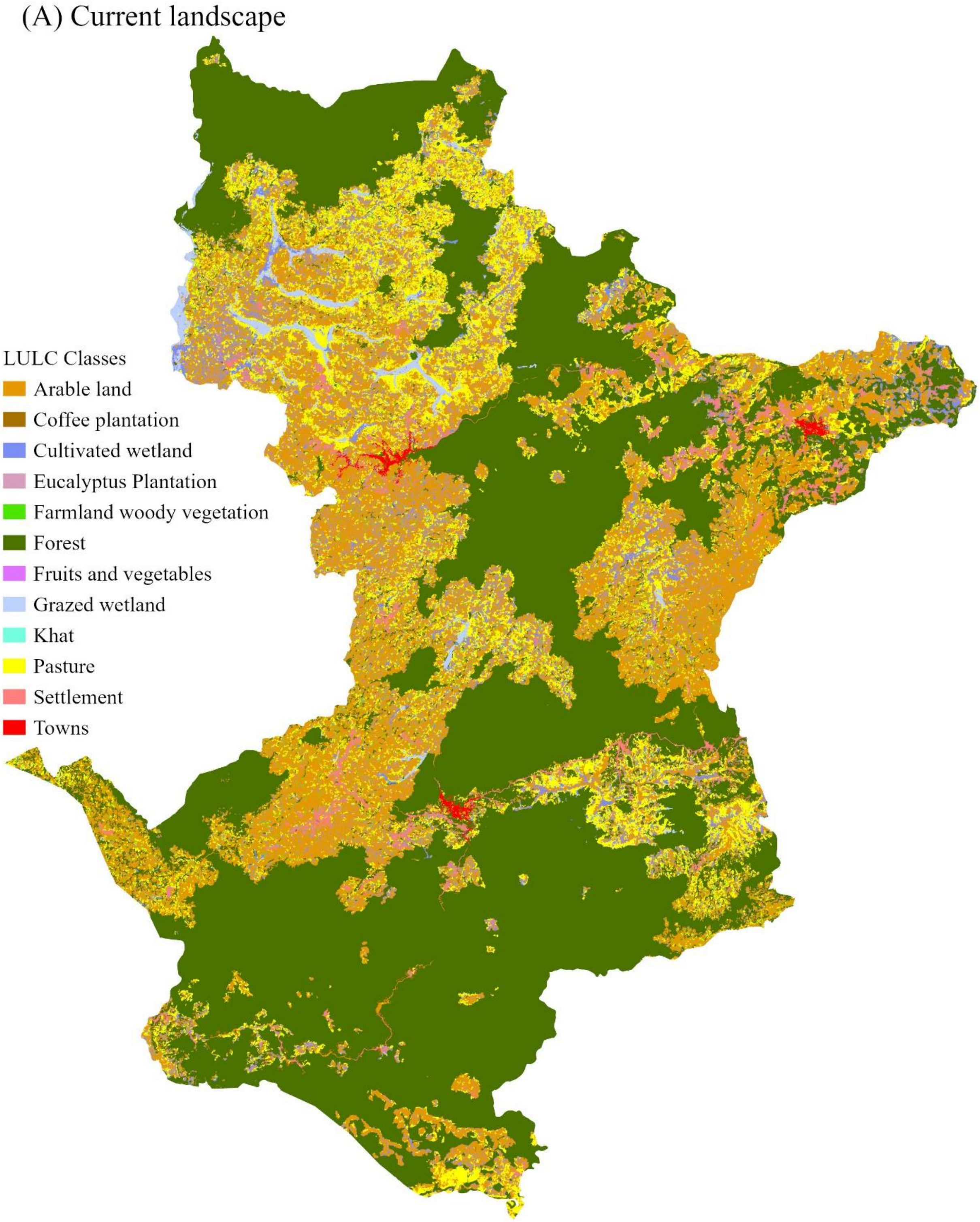
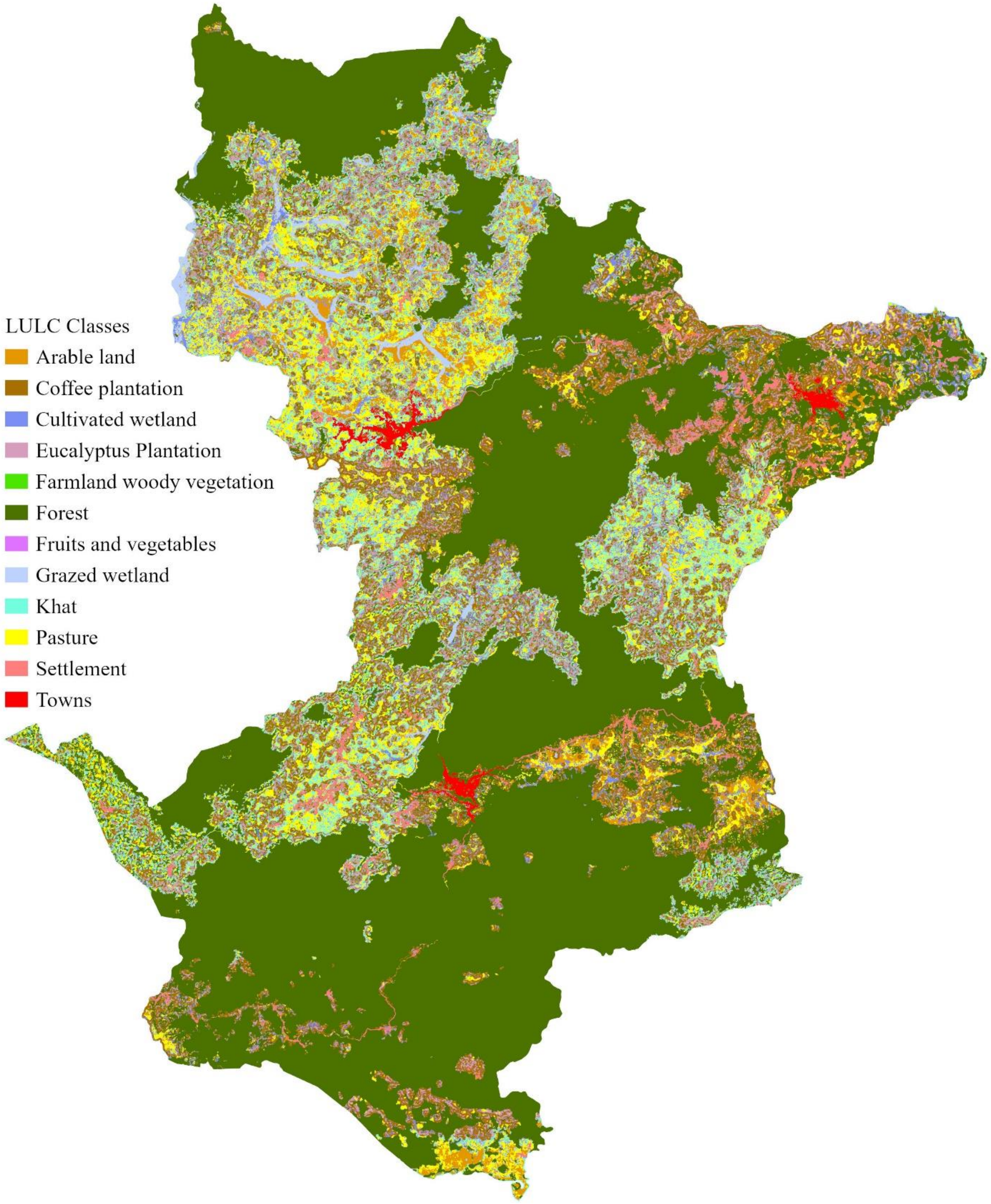
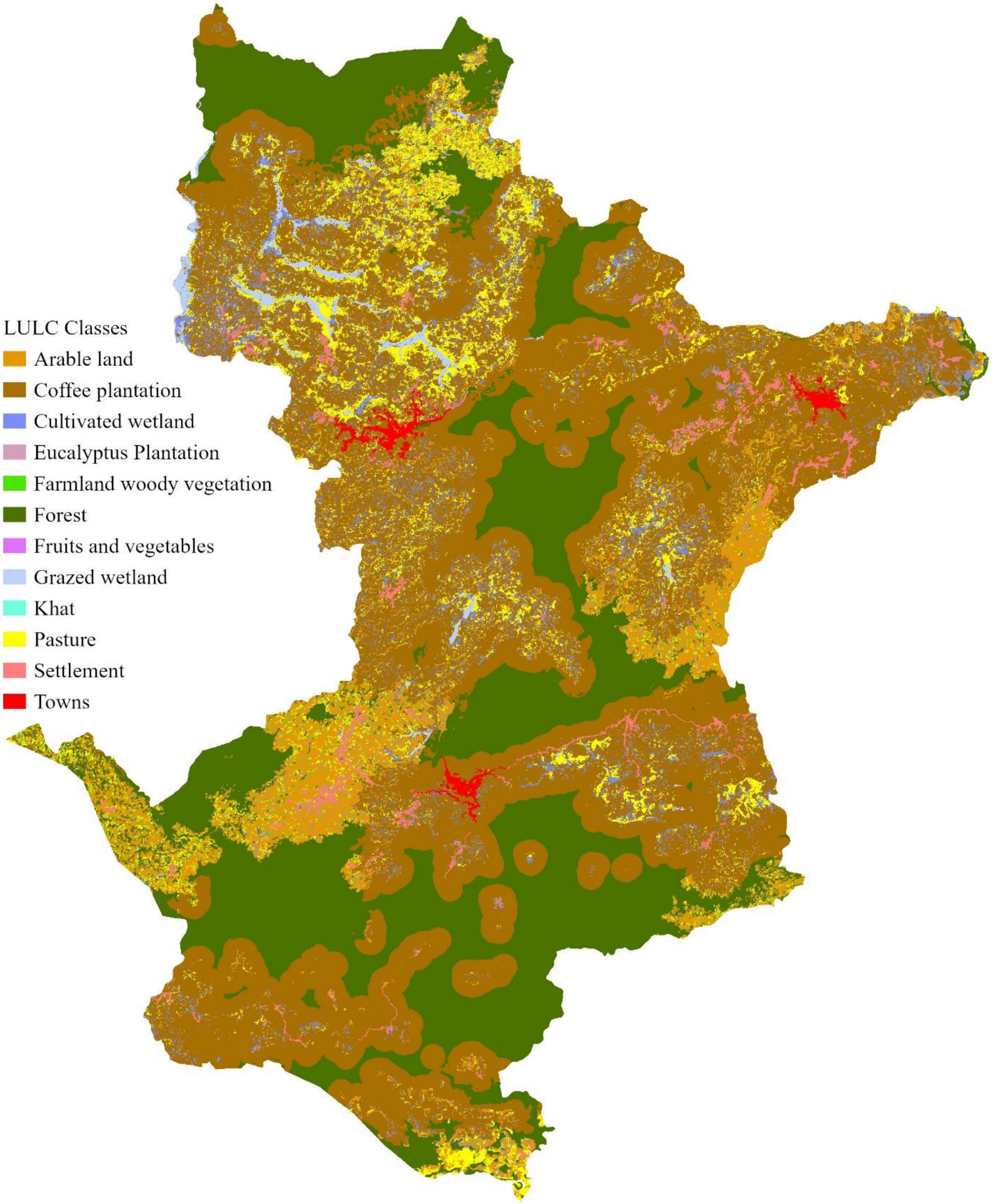


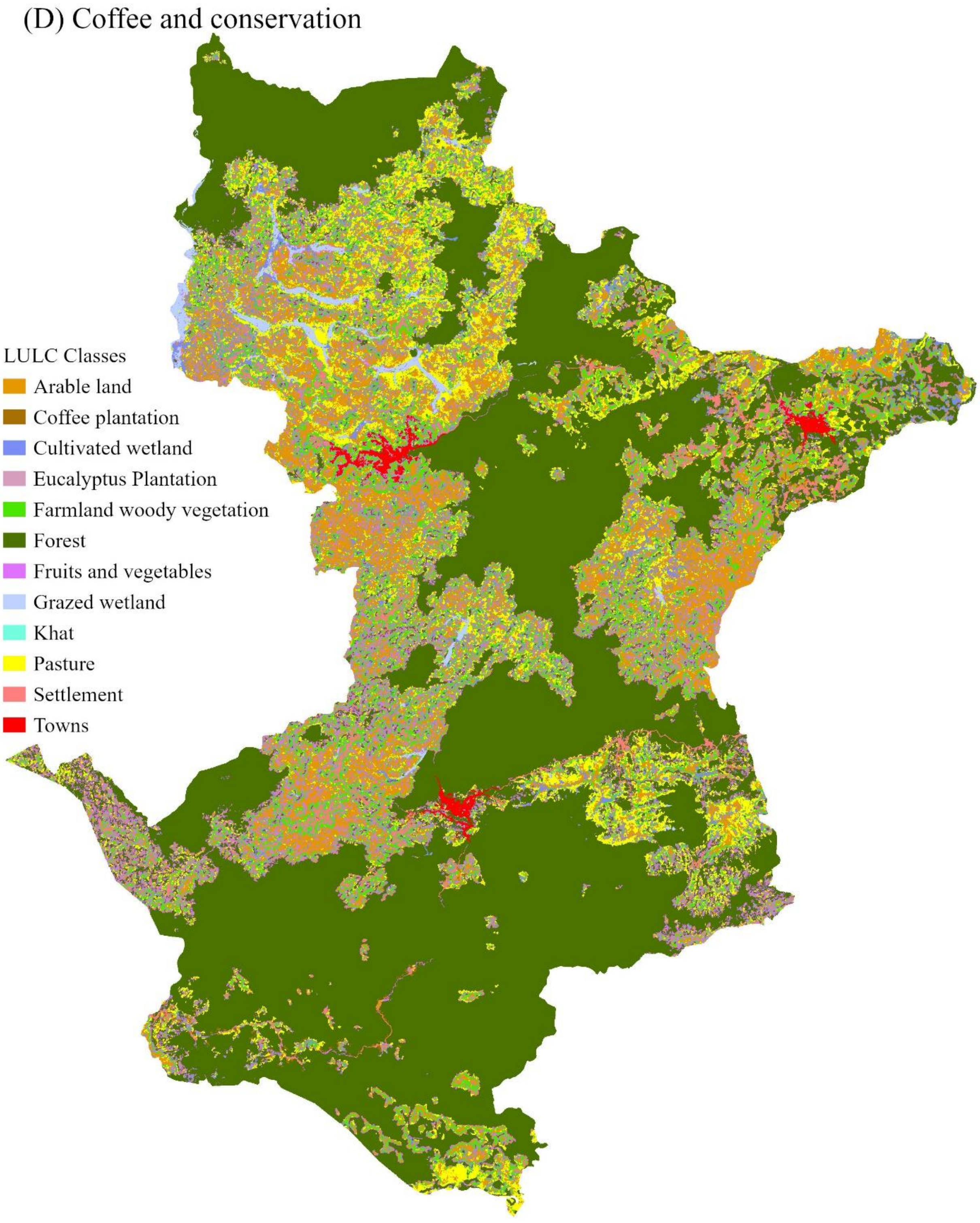
Fig. S2. Spatially explicit, quantitative LULC maps of the current (A) and the scenario (B-E) landscapes (reproduced from (Duguma et al. 2022)) to show the high resolution versions of the maps presented on Fig. 2.

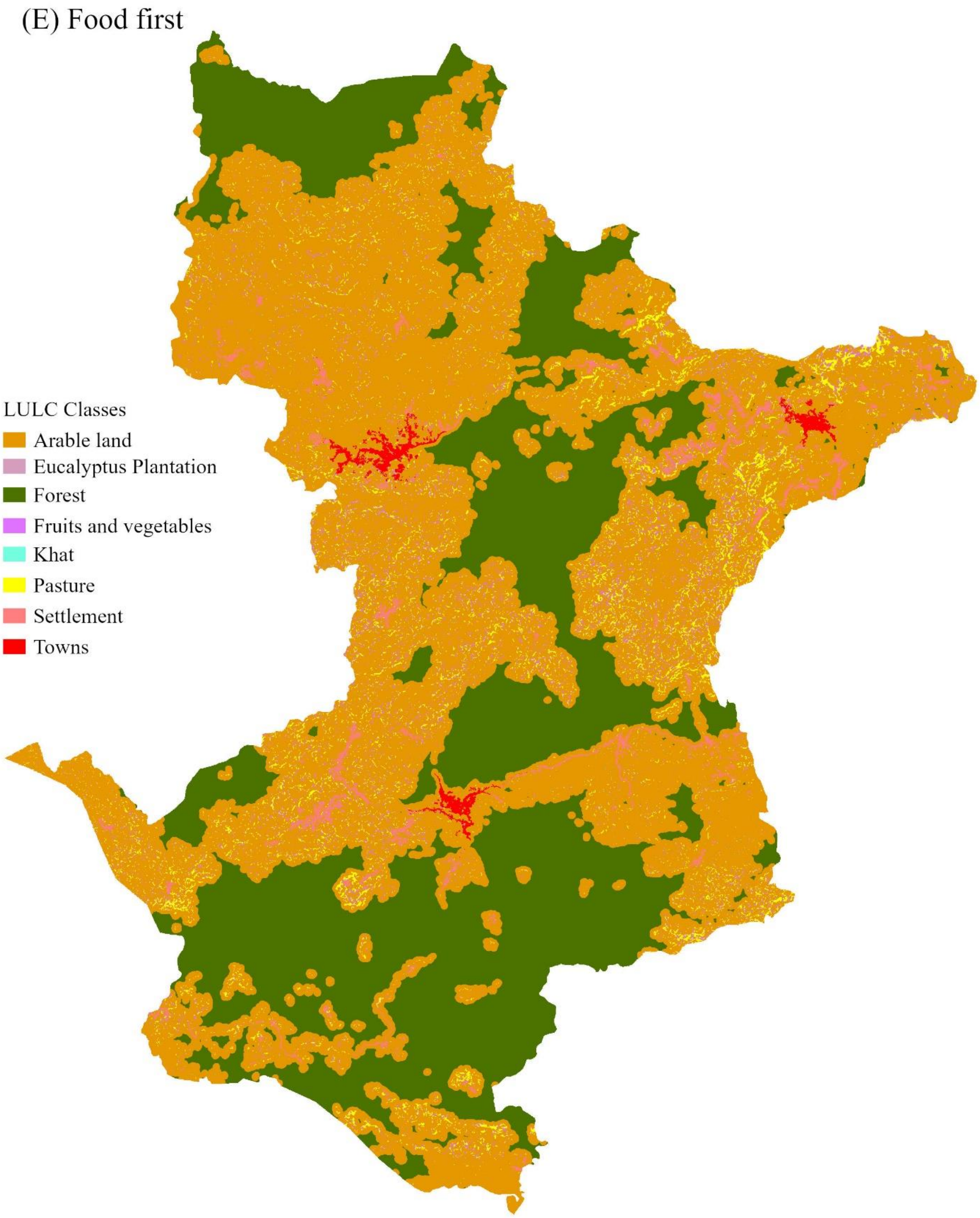




(B) Gain over grain


(C) Mining green gold


(D) Coffee and conservation


(E) Food first

LULC Classes
Arable land
Eucalyptus Plantation
Forest
Fruits and vegetables
Khat
Pasture
Settlement
Towns

Chapter IV

Chapter IV

Land use intensification causes the spatial contraction of woody-plant based ecosystem services in southwestern Ethiopia

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(Manuscript, under revision in Communications Earth & Environment - Nature)

Abstract

Woody vegetation is central for local livelihoods in many tropical landscapes. Sustainable conservation strategies need an understanding of how woody vegetation is used by locals, and how landscape change could influence woody vegetation. Focusing on southwestern Ethiopia, we drew on scenarios that were generated with over thirty local stakeholder groups, as well as on household surveys eliciting how over 90 woody species were used by local people. We combined these to model and predict current and future availability of woody plant-based ecosystem services under four scenarios of landscape change. We show that land-use scenarios with intensified food or cash crop cultivation will lead to the contraction of woody-plant based ecosystem services from farmland to forest patches, implying increased pressure on remaining forest patches. In such a context, attempts to 'spare' forest patches from local people will likely be ineffective, or alternatively, will have serious negative consequences for local livelihoods.

Keywords: access, Afromontane rainforest, ecosystem services, hotspot richness, land sharing, land sparing, land-use scenarios

Introduction

Integrating food production and biodiversity conservation is a pressing challenge across the world [1,2]. Because land-use strategies are central in addressing this challenge [3], one widely used conceptual model to achieve such integration is the ‘land sparing’ versus ‘land sharing’ model [e.g., 4–6]. In land sparing, some areas are strictly protected, while the remaining lands are used for intensive agricultural production [e.g., 5,7]. For a given level of agricultural yield, this approach is particularly useful for protecting species of conservation concern, such as those specialized on largely undisturbed areas of natural vegetation [e.g., 5,8]. Indeed, the importance of near-natural areas for sensitive species has been known for many decades [9,10].

In contrast, land sharing denotes a situation where the equivalent agricultural yield is generated across larger areas. This extensification of agriculture is possibly (but not necessarily) at the expense of strictly protected land [4,11]. Agro-ecological cropping methods including agroforestry, intercropping, conservation agriculture, and mixed crop-livestock systems are examples of land sharing [6,12,13]. Low-intensity agricultural land-use is often very heterogeneous, and this can benefit a wide range of species that are tolerant of medium levels of human disturbance. It can also help to connect forest patches and reduce pressure from the surrounding forest. Highly sensitive species, however, may be absent from such agricultural land because they depend on yet more undisturbed areas [e.g., 5,8].

The challenge of integrating biodiversity conservation and food production is particularly pertinent in the tropics [14,15] – where many landscapes are highly biodiverse, but where local people also strongly depend on local ecosystems and use agrobiodiversity to support their livelihoods [16–18]. In such landscapes, food production levels are clearly important for food security; but beyond that, many other factors also influence the well-being of local people.

One vital factor influencing human well-being is the access local people have to a variety of ecosystem services (ES). Local people's access to ES is limited by spatial characteristics of the services [19,20], the method applied to obtain ES, access to land, technology, capital, and knowledge [21], power asymmetries [22,23] and prevailing development policies [24]. In many smallholder-dominated landscapes in the tropics, many ES are directly used and valued by local people [e.g., 25,26]. Of these services, most are linked to woody vegetation within the landscape [27–29]. Trees and shrubs are used, among other things, as a source of firewood, fodder, construction wood or medicine; to make ploughing tools or household utensils; they can support the production of commodities such as honey or coffee; and some help to maintain soil fertility [e.g., 28–30].

At times when calls are increasing to protect more land for biodiversity conservation – for example through the 30x30 initiative [31] – it is vital to not lose sight of how local livelihoods in the tropics are intimately dependent on the direct appropriation of ES, especially those generated by trees and shrubs within farming landscapes. To that end, spatially explicit maps of tree-based ES under different scenarios of land use change that are based on integrated social-ecological field data could be very useful, but to the best of our knowledge have not been generated to date.

In this paper, we draw on a unique, comprehensive dataset from southwestern Ethiopia (Fig.1), which draws on (i) scenarios of landscape change generated together with over 30 local stakeholder groups; (ii) distribution data of over 33,000 individual stems of trees and shrubs of over 100 species, collected through field surveys, and (iii) detailed information based on household surveys on how local species of trees and shrubs are used as ES by local people. In addition to these datasets, we used a high-resolution land use-land cover map generated from Sentinel satellite imagery. Combining these datasets, we modelled and predicted the current availability of woody-plant based ES in the landscape, and also quantified potential changes thereof under alternative scenarios of landscape change. Following Duguma *et al.* [32], we modelled ES in farmland and forest separately and merged the results. From predicted ES maps, we calculated the richness of ES hotspots – that is, overlaps of (combined) priority areas for different ES – because such areas are especially important for the ongoing provision of services (Fig. 2).

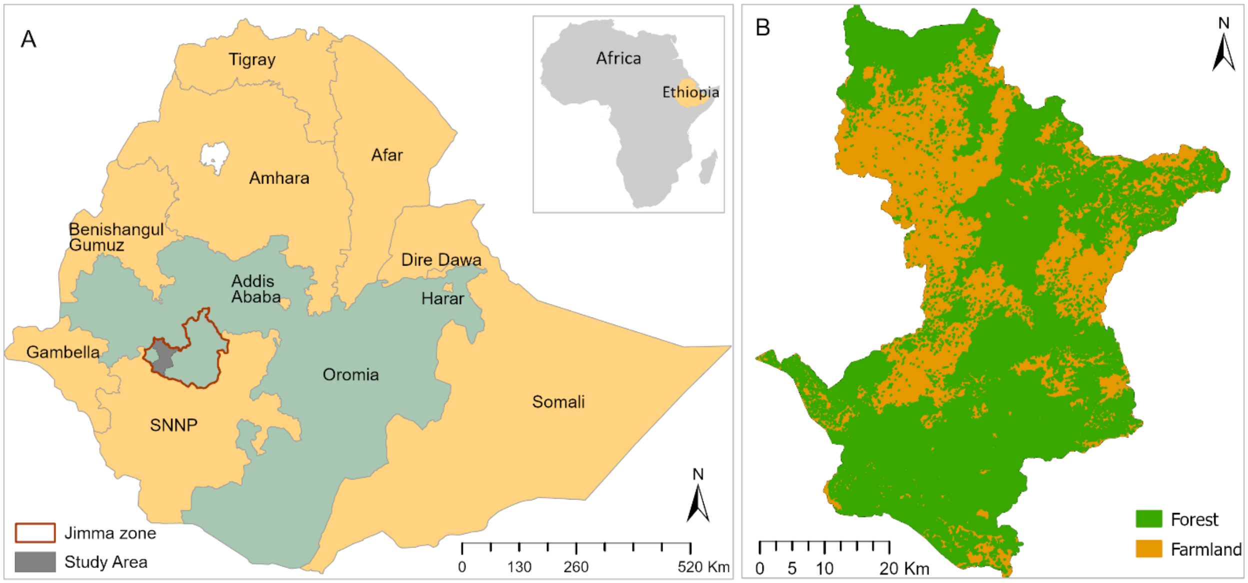

Fig. 1. (A) Study area in Jimma Zone, Oromia, Ethiopia. SNNP stands for Southern Nations Nationalities and People's Region (Central Statistical Agency (CSA) 2007). (B) Present day land cover map that illustrates the distribution of forest and farmland (from (Duguma et al. 2023)).

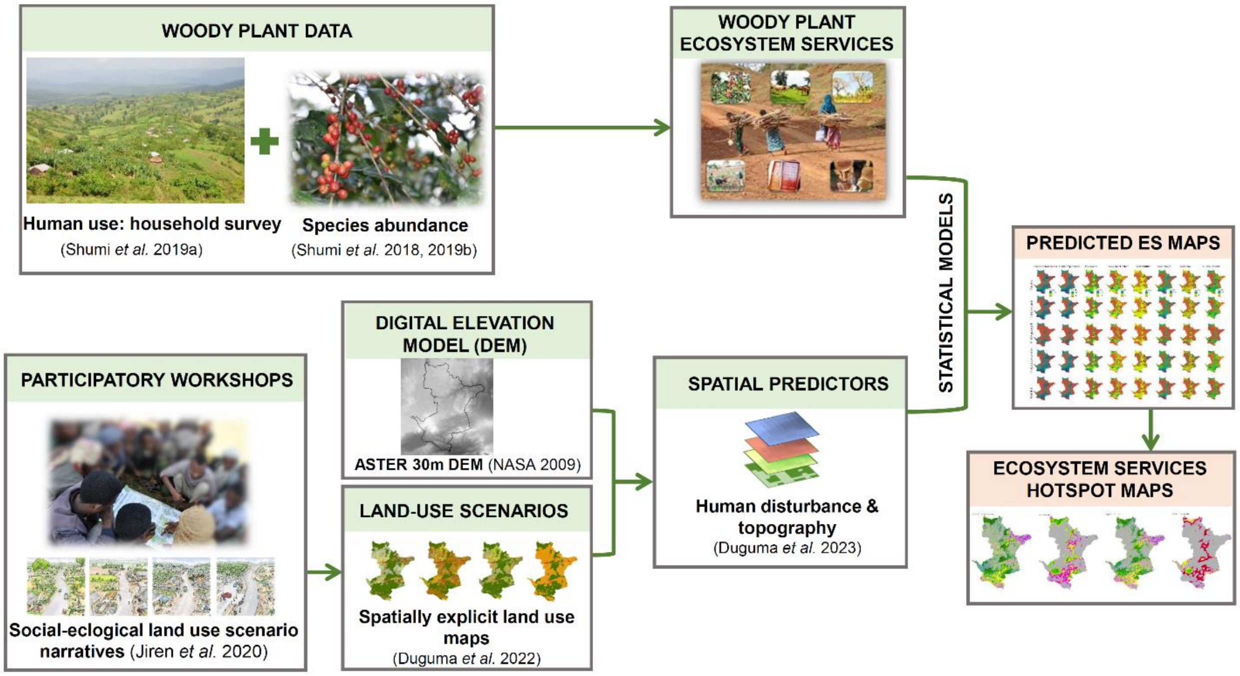

Fig. 2. Overview of our interdisciplinary methodological approach, showing input data (both social and ecological) and methods (photographs taken by Girma Shumi).

Our work shows that conventional agricultural intensification based on land sparing scenarios would cause a displacement of woody-plant based ES from agricultural land to forested areas. Agricultural land-use intensification would thus very likely cause increased exploitation of the remaining forests as a source of vital ES, as well as loss of local access to ES. Such unintended side-effects of agricultural intensification are likely important in many tropical landscapes, and must be considered carefully when making policy recommendations about the integration of food production and biodiversity conservation.

Results

The scenarios

Our study focused on the Jimma coffee forest landscape in southwestern Ethiopia, Jimma zone. Participatory scenario planning was conducted to envision landscape change up to 2040. Thirty-five broadly representative stakeholder groups were involved in scenario development [34], and helped to develop four qualitative narrative scenarios. The resulting scenarios were entitled ‘Gain over grain’, ‘Mining green gold’, ‘Coffee and conservation’ and ‘Food first’ brief summaries in Table 1, for details see [34,35]. The scenarios considered a wide range of plausible environmental, social and economic changes. Two scenarios – namely ‘Gain over grain’ and ‘Coffee and conservation’ – outline smallholder-based development pathways. Both integrate trees and shrubs within the farmland, and do not prioritize large-scale or industrial agricultural practices. In contrast, the scenarios ‘Mining green gold’ and ‘Food first’ imply large-scale and industrialized production of coffee and cereal crops, respectively. As in many other intensively used conventional agricultural landscapes around the world, these scenarios imply a homogenization of land covers, a loss of tree and shrub diversity within farmland areas, and a conversion of small forest patches to intensive farming. Large patches of forest are retained (i.e. “spared”) in both scenarios (Fig. S1). The narrative scenarios were translated into spatially explicit land-use maps based on a current high-resolution land-use map based on Sentinel satellite imagery and rules grounded in the scenario logic. Translation from text to maps considered key features of the scenarios in relation to topography (elevation, slope), farmland heterogeneity as well as proximity to forest edge and roads [35].

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

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.
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.
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.
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 region through intensive, large-scale agriculture, which involves land consolidation, the clearing of woody vegetation, and the expansion of cropland into flat areas and wetlands. Remaining patches of natural forest are strictly protected. Social injustice increases and local and traditional knowledge are eroded.

Woody-plant species and their ES

In surveys of 72 plots in farmland and 108 plots in forest, we identified 128 species of woody-plants. The most dominant species (> 1000 individuals) included *Coffea arabica L., Vernonia auriculifera Hiern., Maytenus arbutifolia (A. Rich.) Wilczek, Justicia schimperiana (Hochst. ex Nees) T. Anders., Chionanthus mildbraedii (Gilg & Schellenb.) Stearn, and Dracaena afromontana Mildbr*. (see [36,37] for details). Drawing on surveys of 180 households, we identified 52 species used for house construction purposes, 38 species for farm implements, 38 species for fuelwood, and 21 species for medicine. Other dominant uses of woody species included the provision of bee forage (20 species), soil fertility (17 species), animal fodder (17 species), and poles and timber (9 species). In each case, specific diameter thresholds were applied, such that for example only individual trees with a diameter (DBH) > 10 cm could be used for poles and timber (for details, see [25]).

We modelled each of these ES (i.e. the number of stems providing a given service in a given vegetation plot) in response to land use, topographic and human disturbance variables, separately in farmland and forest. In farmland, land cover diversity and slope were the most frequently selected predictor variables (seven out of eight models), and elevation was the second most frequently selected variable (four of eight models) (Table 2). In forest, elevation was the most frequently selected variable (six out of eight ES models), and current distance from the forest edge was the second most frequently selected variable (four out of eight models) (Table 3).

Table 2. Modeling results in farmland for woody-plant associated ES. For each ES, the table shows the terms included in the selected model, their coefficients, standard errors, p-values and R^2. All models were negative binomial (model: glmmTMB (truncated >0, negative binomial distribution, link = log, except Poles and Timber, which was modeled with zero inflated negative binomial and negative binomial).

ES	Terms	Coefficients	Std. Error	Pr(>|z|)	R^2
House construction	(Intercept)	5.476	0.114	< 2e-16	0.283
	Elevation	0.267	0.143	0.062	
	Farmland type	0.229	0.119	0.054	
	Land cover diversity	0.518	0.133	9.70E-05	
	Slope	0.417	0.130	0.001	
Farm implements	(Intercept)	2.349	0.302	7.84E-15	0.206
	Farmland type	0.328	0.201	0.102	
	Land cover diversity	0.678	0.215	0.002	
	Slope	0.399	0.224	0.074	
Fuel wood	(Intercept)	5.999	0.103	<2e-16	0.229
	Percent woody vegetation in 2km	0.244	0.120	0.042	
	Slope	0.106	0.119	0.372	
Medicine	(Intercept)	5.550	0.116	<2e-16	0.198
	Elevation	0.290	0.132	0.028	
	Farmland type	0.142	0.121	0.240	
	Land cover diversity	0.234	0.124	0.060	
	Slope	0.304	0.133	0.022	
Poles and timber (Conditional model)	(Intercept)	1.324	0.156	< 2e-16	0.109
	Elevation	0.402	0.186	0.031	
	Historical farmland distance	-0.323	0.152	0.034	
	Farmland type	0.415	0.145	0.004	
	Land cover diversity	0.417	0.162	0.010	
	Slope	-0.488	0.165	0.00314	
Poles and timber (Zero-inflation model)	(Intercept)	-3.790	1038.997	0.997	
	Elevation	1.475	0.749	0.049	
	Farmland type	6.280	2936.430	0.998	
	Percent woody vegetation in 200m	-0.932	0.613	0.129	
	Slope	-1.177	1.511	0.436	
Soil fertility	(Intercept)	5.442	0.206	<2e-16	0.163
	Elevation	0.356	0.205	0.083	
	Land cover diversity	0.212	0.123	0.084	
	Slope	0.229	0.124	0.065	
Bee forage	(Intercept)	4.964	0.132	<2e-16	0.215
	Farmland type	0.236	0.133	0.076	
	Land cover diversity	0.251	0.131	0.055	
Animal fodder	(Intercept)	3.873	0.138	< 2e-16	0.185
	Land cover diversity	0.347	0.133	0.009	
	Slope	0.268	0.152	0.077	

Table 3. Modeling results in forest for woody-plant associated ES. For each ES, the table shows the terms included in the selected model, their coefficients, standard errors, p-values and R^2. All models were negative binomial (model: glmmTMB (truncated >0, negative binomial distribution, link = log, except Poles and Timber, which was modeled with zero inflated negative binomial and negative binomial).

ES	Terms	Coefficients	Std. Error	Pr(>|z|)	R^2
House construction	(Intercept)	5.178	0.063	< 2e-16	0.237
	Elevation	-0.337	0.063	7.31E-08	
	Forest distance	-0.043	0.060	0.473	
	Heat load index	0.122	0.066	0.063	
Farm implements	(Intercept)	2.872	0.059	< 2e-16	0.334
	Elevation	-0.519	0.070	1.03E-13	
	Slope	0.127	0.064	0.045	
Fuel wood	(Intercept)	4.776	0.191	< 2e-16	0.298
	Elevation	-0.625	0.129	1.17E-06	
	Forest distance	-0.235	0.077	0.002	
Medicine	(Intercept)	3.736	0.095	< 2e-16	0.227
	Forest distance	-0.419	0.108	0.0001	
	Forest type	-0.174	0.113	0.123	
	Heat load index	0.361	0.094	0.0001	
	Topographic wetness index	0.216	0.098	0.027	
Poles and timber	(Intercept)	0.799	0.132	1.54E-09	0.301
	Elevation	0.599	0.120	6.31E-07	
	Forest distance	0.302	0.107	0.005	
Soil fertility	(Intercept)	3.222	0.276	< 2e-16	0.236
	Forest type	-0.542	0.148	0.0003	
	Heat load index	0.063	0.087	0.465	
Bee forage	(Intercept)	4.068	0.336	< 2e-16	0.309
	Elevation	-0.953	0.194	9.32E-07	
	Percent woody vegetation in 500m	-0.374	0.119	0.002	
	Topographic wetness index	-0.130	0.110	0.235	
Animal fodder (Conditional model)	(Intercept)	3.538	0.185	<2e-16	0.175
	Elevation	0.187	0.154	0.225	
	Forest distance	0.196	0.101	0.052	
	Forest type	0.237	0.129	0.067	
	Heat load index	-0.151	0.083	0.068	
Animal fodder (Zero-infl. model)	(Intercept)	-17.358	3179.662	0.996	
	Forest type	-7.651	1531.706	0.996	

Change in woody-plant based ES under alternative scenarios

Predicted maps of individual woody-plant based ES revealed a strong effect of land-use scenarios on ES generation (Fig. S2). Hotspots were identified for each ES (detailed in the methods section). The overlay of all ES hotspots produced ES hotspot richness (Fig. 3). In the current landscape, woody-plant based ES hotspots spatially coincided most notably in forest, but numerous ES hotspots also occurred within farmland. The extent of forest (53%) and farmland (47%) in the baseline landscape was approximately balanced [32, Fig. 1(B)].

Under the 'Gain over grain' scenario, ES distributions remained similar to the current landscape. The 'Coffee and conservation' scenario showed an even more dispersed distribution of woody-plant-based ES across the entire landscape compared to the current landscape and the 'Gain over Grain' scenario, with numerous ES hotspots occurring in farmland. The maximum hotspot richness for the current landscape as well as for the 'Gain over grain' and 'Coffee and conservation' scenarios was six. Patterns in ES hotspot richness did not drastically change between the current landscape and the 'Gain over grain' and 'Coffee and conservation' scenarios (Fig. 3, Table S1). In all three landscapes, the highest hotspot richness was found in disturbed forests, in forest edges, and in small forest patches.

Contrary to this, the predicted maps for the 'Mining green gold' and 'Food first' scenarios showed a strongly simplified landscape with distinct and contracted areas in which ES generation was concentrated. Under these two scenarios, hotspot richness increased to up to eight ES hotspots coinciding spatially. At the same time, areas in the landscape that generated not a single ES hotspot also increased (Table S1), and farmland areas generally supported fewer ES hotspots than in the baseline or the other two scenarios.

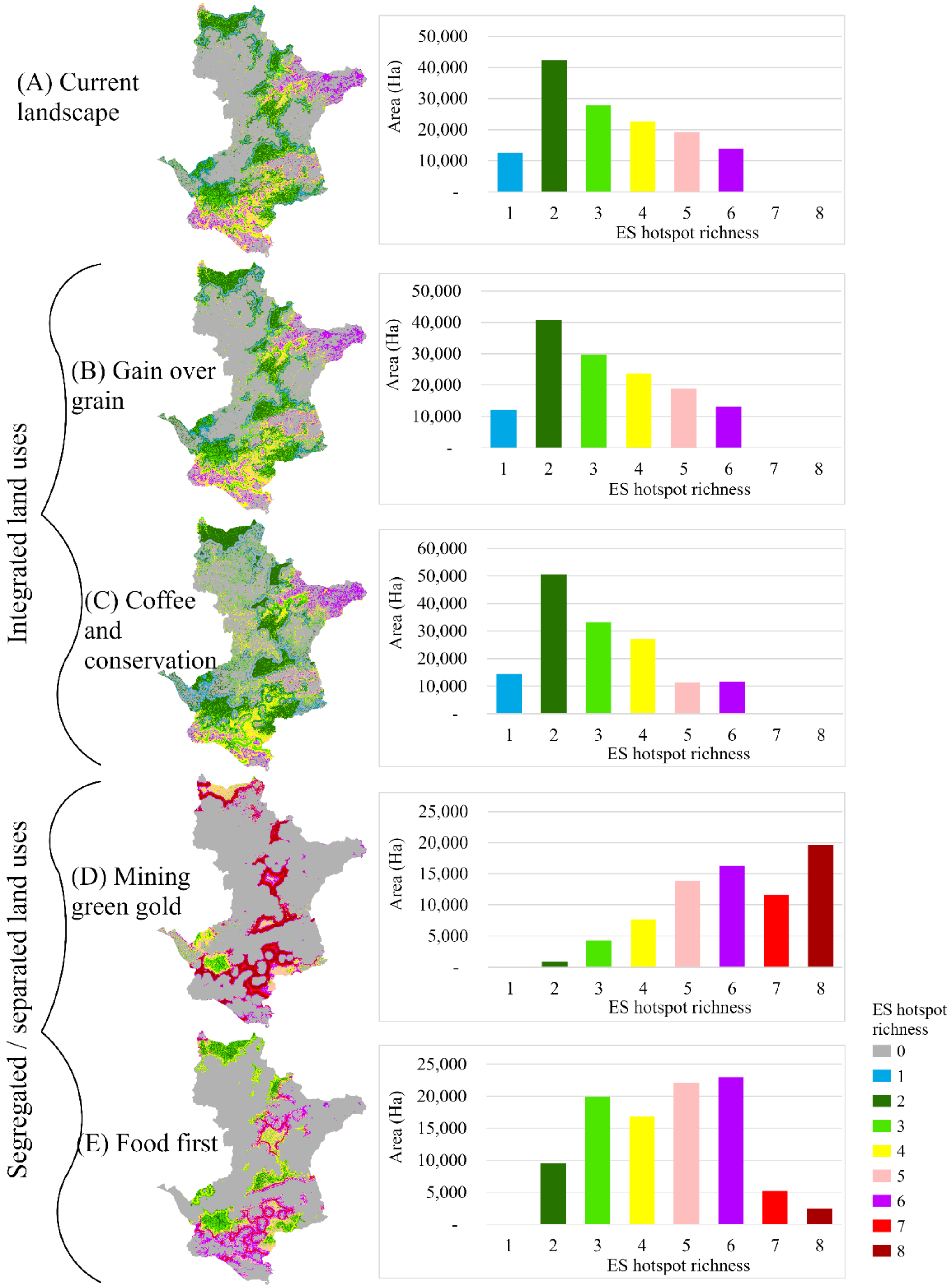

Fig. 3. Richness of ES hotspots for the current landscape and scenarios. ES hotspot richness of 0 (grey in maps) accounted for approximately 51% both in the current landscape and the ‘Gain over grain’ scenario, 47% in ‘Coffee and conservation’, 74% in the ‘Mining green gold’ scenario, and 65% in ‘Food first’ scenario (see Table S1 for details).

Discussion

Our findings show that, for southwestern Ethiopia, intensive agricultural practices – for either cash crops or food crops – would lead to a contraction of woody-plant based ES, from a mixture of farmland and forested areas to remnant forest patches. Assuming local people need access to these ES, these results imply both a decrease in local accessibility to ES and increased pressure on remaining forest patches in scenarios of agricultural intensification. The effectiveness of sparing such patches from human influence, in this context, is questionable from a practical perspective, and could have significant negative implications for local livelihoods. We showed this using an analysis of ecosystem service hotspot richness for the present landscape and four future socio-economic land-use scenarios. Below we discuss our findings in detail, first in the context of the current landscape, then for the land-use scenarios, and against the backdrop of land sharing and land sparing approaches.

Current landscape context

In the current landscape, the highest hotspot richness was found mostly at the edges of forest, in small patches of forests and in disturbed or fragmented forests (Fig. 3). This coincides with locations that the local community can easily access. At present, the landscape is characterized by a forest and farmland mosaic dominated by smallholder farmers, whose main economic activities are dependent on subsistence agriculture, livestock rearing and coffee production [26,29]. Even though the forest is formally owned by the state, local people have access rights to ES generated from the forest through different mechanisms such as customary mechanisms and inheritance [e.g., 28,38] as well as historically developed social standards and norms [e.g. 38].

Compared to the past, present access to ES generated from woody plants is more constrained due to a decrease in forest extent [26,32,39]. Additional factors that can constrain current access for different community members to ES are distance to forest, rules and regulations on forest governance such as an increased protection status of the forest, forest ownership, and property rights and tenure insecurity [e.g., 25,26,40]. Such factors that modify access are also found elsewhere. For instance, in the Solomon Islands, physical availability (e.g. quantity, quality and location/distance) and rights regarding appropriation and management are some of the main factors limiting access to ES [20], while in Nepal, restricted collection period/time (i.e., Dec-Jan, and May-Jun) of forest products from community forestry is one of the limiting factors identified for access to ES [22]. In addition, local communities' access to ES can be limited by power relationships, information, technology, tools and markets [21,23]. With these factors that shape access in mind, we discussed below how land-use scenarios affect woody-plant based ES distribution, and how this in turn is likely to influence local access to ES.

"Land sharing" scenarios: Gain over grain and Coffee and conservation

The 'Gain over grain' scenario showed a similar distribution of ES hotspots as the current landscape. This similarity exists because the extent of farmland woody vegetation and forest area remained unchanged relative to the status quo in this scenario, while specialization in commercial cash crops took place on farmland [34]. These cash crops – namely coffee, khat and eucalyptus – could potentially increase the income of smallholder farmers [e.g., 34,41,42].

Despite this possible advantage, evidence suggests that eucalyptus plantations, for instance, which were established to substitute for woody-plant based ecosystem service losses in the past due to deforestation, could not adequately substitute the full suite of ES generated from native forest trees [39]. Indeed, specialization on cash crops in the farmland could have negative effects in the long term because agrochemical use is common for such crops in Ethiopia [e.g., 41,43]. Furthermore, cash crops such as khat have a potential to cause social disorder (such as conflict, crime, and mistrust) that affect local traditions [34,43]. In addition, as more farmland is occupied by cash crops, local community may face food insecurity and low dietary diversity because of a lack of food crops. Finally, under this scenario local community could encounter similar access issues to woody-plant based ES as in the current landscape, relating to the physical distribution of the forest, rules and regulations on forest governance, property rights and tenure insecurity (see previous section).

The ‘Coffee and conservation’ scenario also showed a degree of similarity with the current landscape in ES hotspot distribution. Under this scenario, the area in the landscape that generated no woody-plant based ES decreased. ES hotspots in this scenario were more widely distributed in the landscape due to restoration and regeneration of degraded farmland in this scenario [34,35]. At the same time, the area that generated high levels of many ES simultaneously (i.e., five or six ES) was also reduced, indicating that forests in this scenario may be under less intense human pressure than presently.

Farmland heterogeneity is widely acknowledged to be key for restoring and sustaining farmland biodiversity [44], and as we show here, also underpins the availability of many woody-plant based ES. In addition to absorbing pressure from the forest, based on physical availability and distribution of forest and woody plants, this scenario would likely increase access to ES for the local community.

One possible limitation of this scenario is that farming on degraded steep slopes was replaced by regeneration and restoration of woody plants, which could, in the short term, reduce food availability. Similar trade-offs have been acknowledged in different parts of the world as a challenge for integrating farming and conservation [e.g., 1,6]. In the long run, however, biodiversity-friendly farming as implied in this scenario may be most suitable to ensure social-ecological resilience.

"Land sparing" scenarios: Mining green gold and Food first

'Mining green gold' and 'Food first' were based on land-use intensification involving large-scale land consolidation and mechanized farming for coffee plantation and food crops, respectively [34]. In both scenarios, no integration occurred of food production and biodiversity conservation, and remaining forest patches were to be "spared" through strict regulations limiting access for local communities.

Compared to the current landscape, these scenarios revealed strong changes in ES hotspot richness; richness increased in the smaller available area and contracted to the center. This effect occurred because of a decrease in the total amount of woody vegetation, including its widespread loss in farmland, as well as a contraction of near-natural forest patches. The contraction of woody-species based ES hotspots could increase the distance and time for many local community members to access woody-plant based ES; as well as putting potentially high levels of pressure on the remaining forest patches.

Similar findings elsewhere, for instance in Argentine Chaco, showed widespread and major losses in multiple ES as a result of agricultural expansion into forests [45]. Moreover, "land sparing" caused negative impact on human well-being in Brazil Para [46], and has already been shown to reduce access to important provisioning ES in southwest Ethiopia [e.g., 28,39]. While both physical and legal factors could limit access to ES by the local community, such strict protection of remaining forest is vital for the conservation of native species in the context of a "land sparing" strategy [5,8,47].

Further, the production method used in these two scenarios – industrialized production including agrochemical inputs and large-scale investors – in itself is likely to cause problems for farmland both on biodiversity and many smallholder farmers. Previous studies on large-scale agricultural intensification, for instance, on socioeconomic outcomes in Southeast Asia [48], deforestation patterns in Cambodia [49], or impacts on indigenous communities in Ethiopia [50] and Rwanda [51] have consistently shown that many local stakeholders were excluded from the potential benefits of increased production. The two scenarios do, however, have potential benefits for the Ethiopian economy at large, for example through generating incomes from exports [34].

Finally, several studies elsewhere in the world, for example, in Southeast Asia, revealed that yield increase by agricultural intensification stimulated further agricultural encroachment [e.g., 52,53] rather than the strict protection of remnant forest. Conversely, if strict protection of remaining forest patches is indeed successful, this very likely would exacerbate existing inequalities in access to ecosystem services [26]. The two intensification-based scenarios considered therefore may not lead to the effective "sparing" of remaining forests, or if sparing is successful, community well-being may be seriously impaired due to reduced access to woody-species based ES.

General implications

Our work represents a systematic evaluation of future land-use strategies on long-term ecosystem service provisioning that could guide land-use management policies for integrated biodiversity conservation and sustainable development in smallholder farming landscapes. In a heterogeneous world, land-use choices must take into account circumstances depending on spatial characteristics, actors' rationalities, local contexts and socioeconomic dynamics [53]. We may need both land sharing and land sparing in different contexts and to different extents – because both have individual and complementary benefits but also shortcomings [4,6]. As land sparing literature has shown, forest matters for biodiversity, especially for the conservation of rare or otherwise sensitive species. But agricultural land has important complementary values for biodiversity, and can be critical, as we showed here, for the generation of ES that are vital for local people. Considering the dependence of local people on woody-plant based ES is vital in many landscapes of the Global

South in particular. If local needs for woody-plant based ES are not considered in conservation planning, conservation measures will most likely not be successful, because people are likely to go into the forest and then illegally extract these ES from the forest out of necessity.

Methods

Our methodological approach was interdisciplinary. It involved the integration of different disciplinary data – participatory scenario narratives developed with local stakeholders, spatially explicit land-use and land cover maps based on the narrative scenarios, data on woody-plant use collected via a household survey, 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 land-use and land cover maps (Fig. 2). We used ArcGIS Pro and R to integrate and analyze the data. We statistically modelled individual ES, predicted the selected models spatially, extracted individual ES hotspots and aggregated ES hotspots to produce ES hotspot richness map. Details are explained below.

Study area

Our study focused on the Jimma coffee forest landscape in southwestern Ethiopia, Jimma zone. The area is characterized by a forest and farmland mosaic dominated by smallholder farmers, whose main economic activities are cereal crop production, livestock rearing and coffee production. The study area is undulating, and falls within altitudes of approximately 1200 to 3000 m above sea level. We used the classification of farmland and forest [32] to separately model ES in farmland and forest, because different drivers operate in these two very different environments. Modelling results were finally merged for the whole landscape.

Data

Datasets used for our study were indicated in Fig.2. Briefly, two datasets were used to model potential ES provided by woody-plants: field data on woody-plant use and woody-plant species (the outcome variable) and spatial predictor variables (indicators of human disturbance and topographic variables).

ES by Woody-plants

We surveyed woody plants in 72 individual 1 ha plots in farmland and in 108 individual 20 m by 20 m plots in forest [25,37]. Use of woody-plant based ES was assessed from 180 randomly selected households [25]. For this study, of eleven major uses delivered by over 100 woody-plant species, we focused on eight ES which we considered most important ones in the daily lives of local community [e.g., 28–30]. These were house construction, farm implements, fuel wood, bee forage, medicine, poles and timber, soil fertilization, and animal fodder. Detailed descriptions and definitions of these response variables are available in supplementary material Table S2 [29]. We used woody-plant species abundance to quantify and map the potential ES provided by woody plants (individuals of tree and shrub species with a height >= 1.5 m, diameter thresholds varying for each ES (Table S2)). Abundance was estimated within 20 m by 20 m plots in forest, and 1 ha plots in farmland. Farmland results were downscaled to 20 m by 20 m before merging forest and farmland results across the entire landscape. Thus, results were expressed as the number of individual trees potentially providing a particular ES within each 20 m by 20 m pixel across the entire landscape.

Candidate predictors

Fifteen candidate social-ecological predictors were identified based on our knowledge of the landscape, the ES considered, and literature on drivers of ES [e.g. 54,55], as well as data availability for the baseline and future scenarios. These included both topographic variables and indicators of human disturbance. Details of predictor variables were presented in [32] and in Table S3. Predictor variables were examined using histograms, transformed where required, and center-scaled. After problematic variables were removed, we used VARIMAX rotated PCA to identify the five dominant uncorrelated dimensions of the predictor variables.

For farmland, this process selected elevation, slope, percent woody vegetation (in a 200 m radius), landscape diversity (at 1 ha), and the historical (1985) distance to the forest edge. Elevation was found to correlate positively with current distance to forest edge, and negatively with landscape diversity (at 1ha) and percent woody vegetation (in both a 500m and 2km radius). Slope was correlated positively with heat load index, topographic roughness, and negatively with topographic wetness index. We also included the binary variable of farmland age (extant prior to 1985).

For forests, this process selected current distance to the forest edge, slope, elevation, heat load index, and topographic wetness index. Current distance from the forest edge was positively correlated with percent woody vegetation (at 500m and 2km radius), slope was positively correlated with roughness, and elevation was positively correlated with historic (1985) distance to the forest edge. We also included the binary variable of forest age (extant prior to 1985).

Model selection and spatial prediction

We used generalized linear models due to their direct interpretability, which facilitate supervised model assessment. We selected separate models for each ecosystem service in each habitat by first assessing the full model (i.e. a linear additive combination of the selected predictors) with Poisson and negative binomial distributions, both without and with zero inflation (with the zero inflation echoing the core full model) (glmmTMB) [56]. Where these full models had convergence issues, we iteratively removed parameters (starting with those with the largest absolute coefficients) until there were no further issues. We assessed these models for zero-inflation, dispersion, and AIC. For the selected models, we then reduced the number of variables in each model by comparing all combinations of sub-models based on AICc (MuMIn) [57]. The top 5 models were then compared using repeated cross-validation (10 fold, with 3 repeats) and metrics of root mean squared error, explained deviance (R squared), and mean average error [yardstick; 58]. We then performed checks of model residuals (DHARMa) [59]. Where this process did not produce satisfactory models, we also assessed models that used alternative predictors, removed extreme outliers, and/or included quadratic terms on elevation. We conducted modelling in R v 4.1.2 [60], including the packages mentioned above. Spatial prediction was done using the "terra::predict" in R package terra [61]. We mapped each ES for farmland and forest separately and merged the results to the landscape scale.

ES hotspot richness

We used a hotspot analysis approach following [62] and [63] to identify areas important for ES. We defined hotspots as pixels in the upper 20th percentile of values of areas in the landscape for each potential ES. To arrive on the 20th percentile we used a quantile classification approach for individual ES at a cut threshold of 80% in R software. The upper 20th percentile was extracted to represent the hotspot of each ES in ArcGIS Pro2.9. This approach is an effective and simple way to identify areas with a high priority for long-term ecosystem service maintenance [63] and is useful to communicate findings to stakeholders. Finally, we overlaid hotspots of individual ES to map the richness of ES hotspots. Based on this, we evaluated changes in ES hotspot richness under the four scenarios relative to the current landscape.

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Supplementary materials

Table S1. Area coverage of ES hotspot richness for the current landscape and scenarios. (ESHR = ES hotspot richness, CL = Current landscape, and for scenarios: GG = Gain over grain, MGG = Mining green gold, CC = Coffee and conservation, FF = Food first). Proportion of each ES hotspot richness is indicated in percentage in brackets.

	Area (in hectares)				
ESHR	**CL**	**GG**	**MGG**	**CC**	**FF**
0	143,146 (51%)	143,287(51%)	207,422 (74%)	133,137 (47%)	182,664 (65%)
1	12,571 (4%)	12,137 (4%)	52 (<1%)	14,521 (5%)	15 (<1%)
2	42,278 (15%)	40,881 (15%)	877 (<1%)	50,585 (18%)	9,554 (3%)
3	27,880 (10%)	29,695 (11%)	4,326 (2%)	33,251 (12%)	19,906 (7%)
4	22,761 (8%)	23,778 (8%)	7,675 (3%)	27,249 (10%)	16,814 (6%)
5	19,139 (7%)	18,876 (7%)	13,875 (5%)	11,364 (4%)	22,079 (8%)
6	13,945 (5%)	13,066 (5%)	16,302 (6%)	11,613 (4%)	22,998 (8%)
7	-	-	11,602 (4%)	-	5,240 (2%)
8	-	-	19,589 (7%)	-	2,450 (1%)

Table S2. List of woody-plant associated ecosystem services, including description and threshold size (Shumi et al. 2019a, 2021)

Use/purpose		Description	Threshold
House construction	House wall and roof construction	Wood used for wall and roof construction	DBH ≥ 5 cm
	Wall and roof fixing	Small wood used for fixing wall and roof	Any size (can be split)
Farm implements	Handle	Wood used as beam handle for ploughing	DBH 5–10 cm
	Yoke	Wood used as yoke for ploughing	DBH 10–30 cm
	Beam	Wood used as beam for ploughing	DBH 10–20 cm (can be prepared)
Fuelwood	Firewood and charcoal	Parts (leaf, bark or wood) of trees/shrubs used for cooking, lighting and heating	Any size (can be split)
Honey production	Bee forage	Shrub/small trees suitable for bee forage	Any size
		Large/old trees suitable for bee forage	DBH > 10 cm
Medicine		Parts (leaf, bark or wood) of trees/shrubs used for healing human or animals	Any size
Soil fertilisation		Trees/shrubs contributing to soil fertilisation	Any size
Animal fodder		Parts (leaf, twigs or bark) of trees/shrubs used as animal fodder	Any size
Poles and timber		Wood used for poles and timber	DBH ≥ 10 cm

Table S3. Variables used in the model building process, taken from (2023), except Tin roof density.

Variables	**Source**	**Included in farmland models**	**Included in forest models**
Elevation	ASTER 30m DEM	Yes	Yes
Farmland type - primary farmland or new farmland	Derived from LULC map generated from Landsat (1985) and Sentinel (2019)	Yes	No
Current farmland distance from the forest edge	generated from LULC map	Yes	No
Historical farmland distance	generated LULC map of 1985 from forest edge	Yes	No
Forest type - Primary (pre-1985) or secondary forest (newly occurring since 1985)	Derived LULC map generated from Landsat (1985) and Sentinel (2019)	No	Yes
Current forest distance from the forest edge	generated from LULC map	No	Yes
Heat load index	Derived from ASTER DEM (Olsson et al. 2009)	Yes	Yes
Percent woody vegetation within a 1 ha (56 m radius) moving window	generated from LULC map	No	No
Percent woody vegetation within a 2 km radius moving window	generated from LULC map	Yes	Yes
Percent woody vegetation within a 500 m radius moving window	generated from LULC map	No	No
Land cover diversity within 1 ha	generated from LULC map, using Simpson’s diversity index in Fragstats 4.2 (McGarigal and Ene 2015) of land covers.	Yes	No
Land cover diversity within a 200m radius	generated from LULC map, using Fragstats 4.2 Simpson’s diversity index (McGarigal and Ene 2015) of land covers.	Yes	No
Slope in degrees	Derived from ASTER DEM	Yes	Yes
Topographic wetness index	Derived from ASTER DEM using ArcGIS	Yes	Yes
Tin roof density	Derived from tin roof points using point density in ArcGIS	Yes	Yes

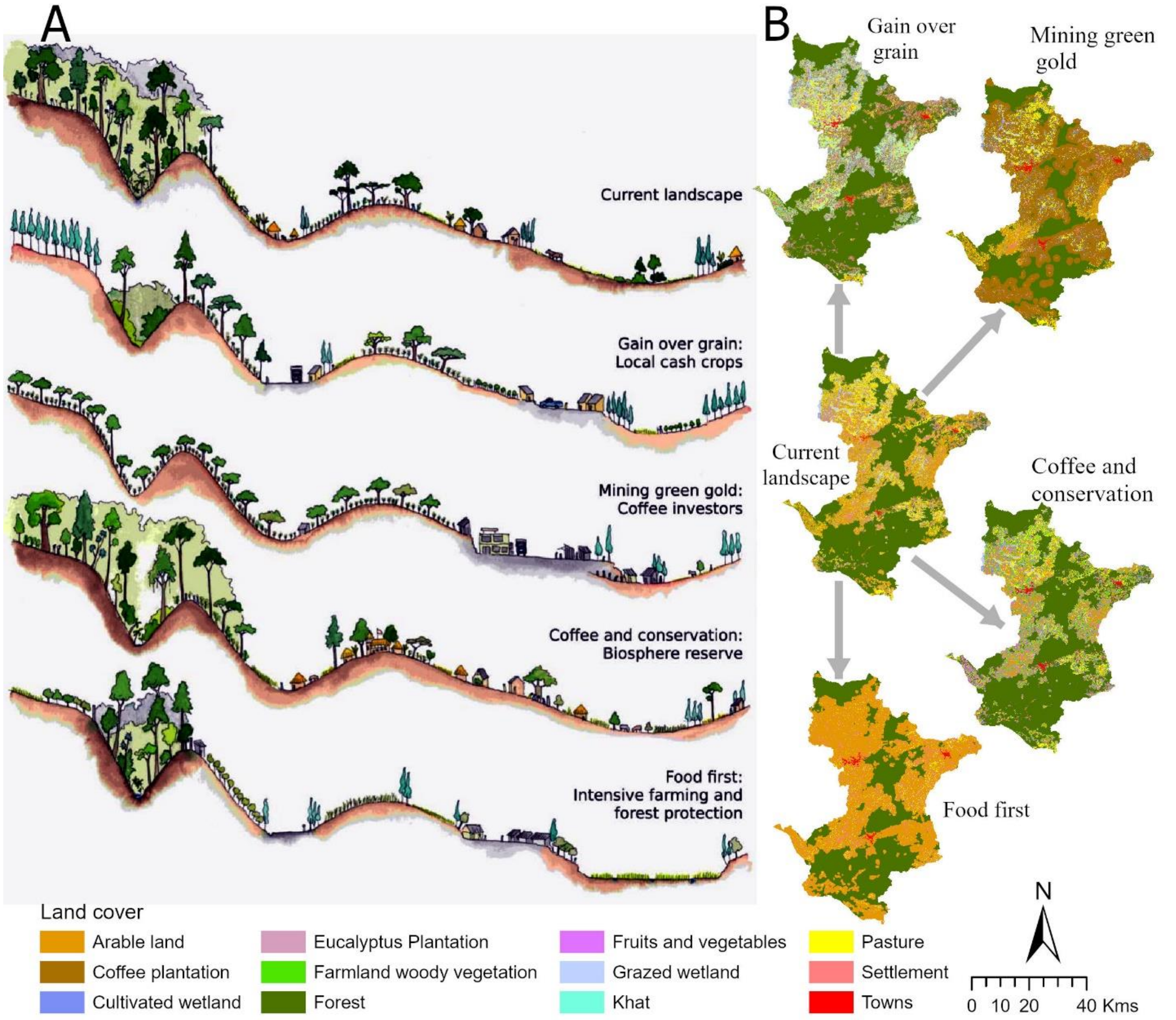

Fig. S1. (A) A cross-sectional illustration of the present landscape and the four scenarios (reproduced from Jiren et al. 2020), and (B) spatially explicit, quantitative LULC maps of the current and the scenario landscapes (reproduced from (Duguma et al. 2022)).

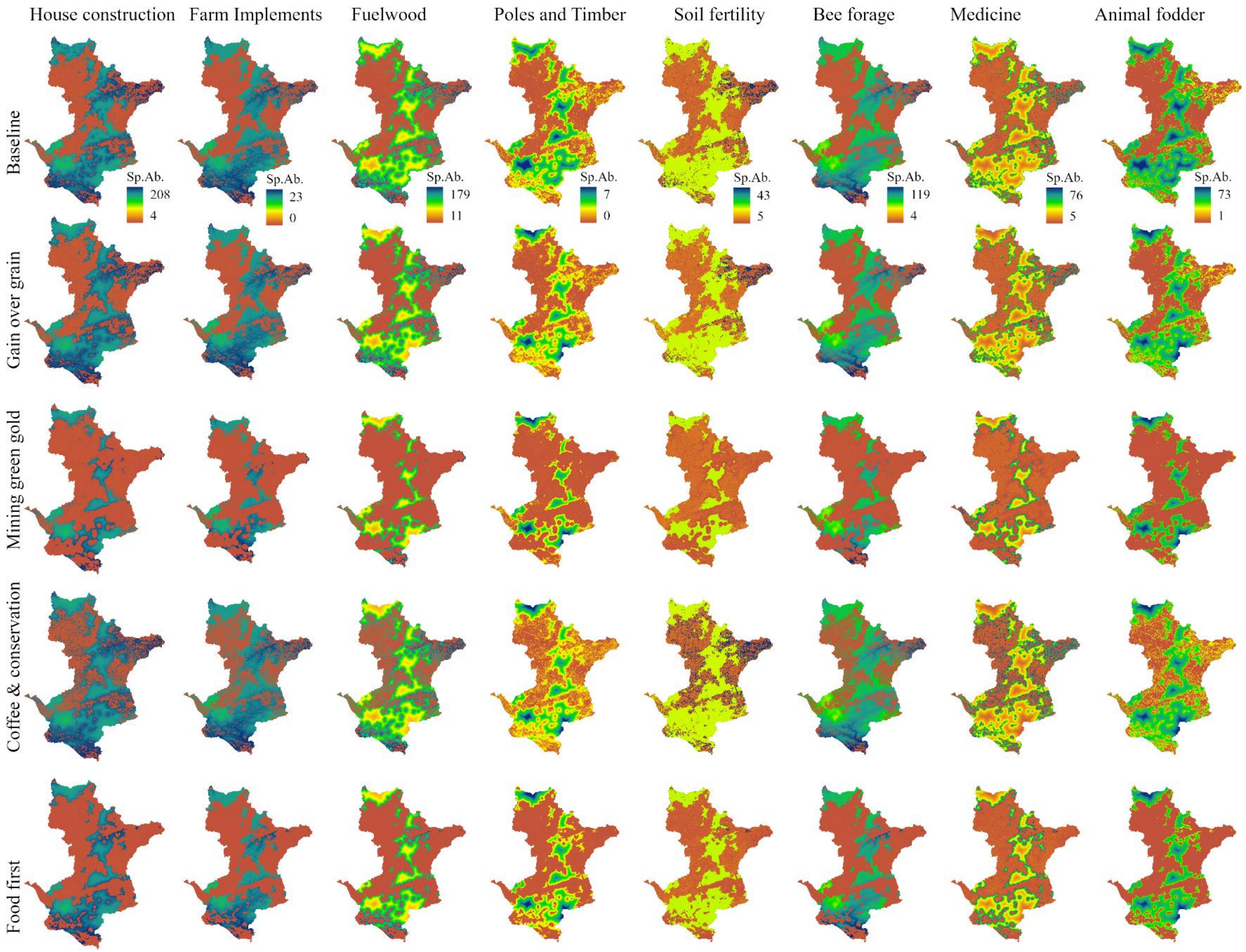

Fig. S2: Predicted ES for the current landscape (baseline) and scenarios for eight ES considered in this study.

Chapter V

Chapter V

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 biodiverssity conservation (Fischer et al. 2013; Kremen 2015; Mehrabi et al. 2018b).

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. 2022b). 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 km^2. 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.

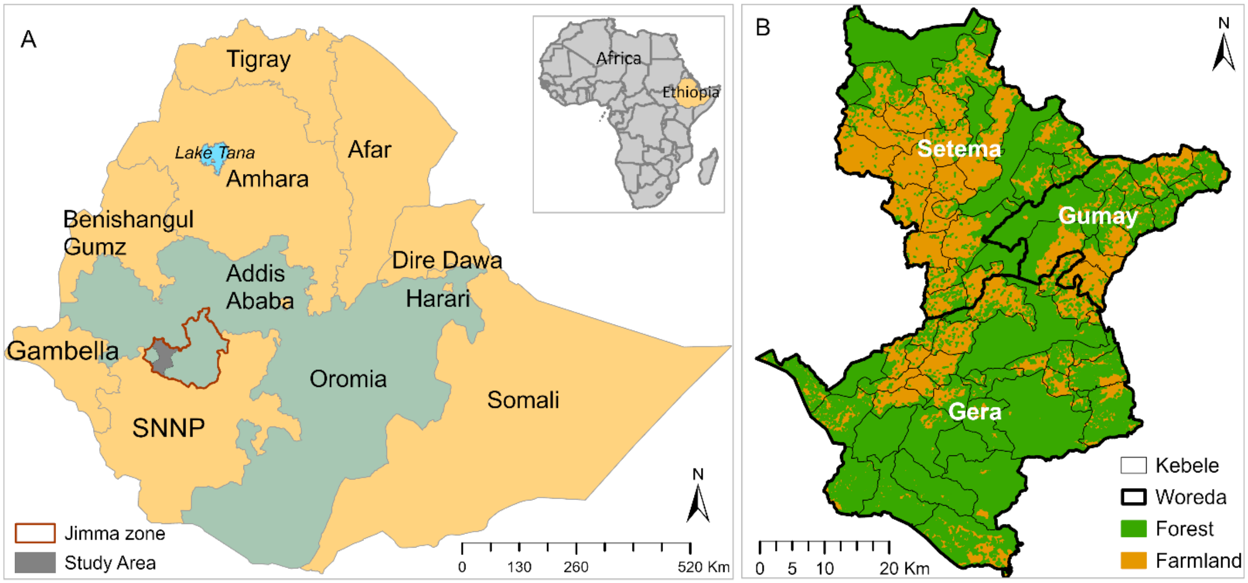

Fig. 1. (A) the study area in Jimma Zone (grey), Oromia region (green grey) within Ethiopia (other regions are tan-colored); (B) the district boundaries (woredas; delimited by a thick black line and labelled in white) and lower administrative boundaries (kebeles; thin black lines) in the study area. 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).

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)

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).

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.

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 conservation'	'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**

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 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 landscape	‘Gain over grain’	‘Coffee and conservation	‘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.

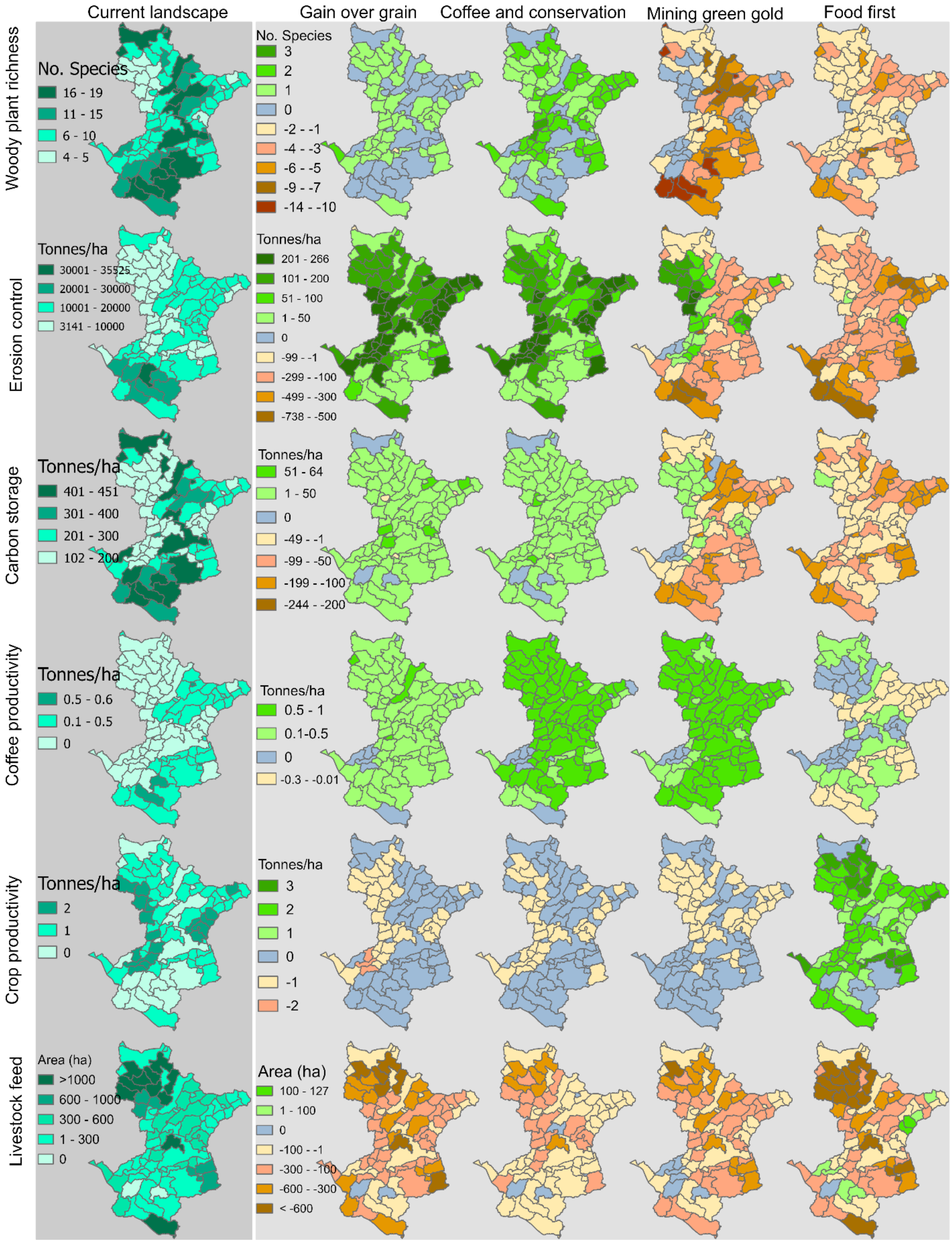

Fig. 2. Potential ES maps and changes at the kebele level. The left column shows current ES potentials. The other columns show changes for the scenarios. Orange shades in the right panel indicate a decrease in a given ES, whereas green shades indicate an increase; blue indicates no change relative to 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.

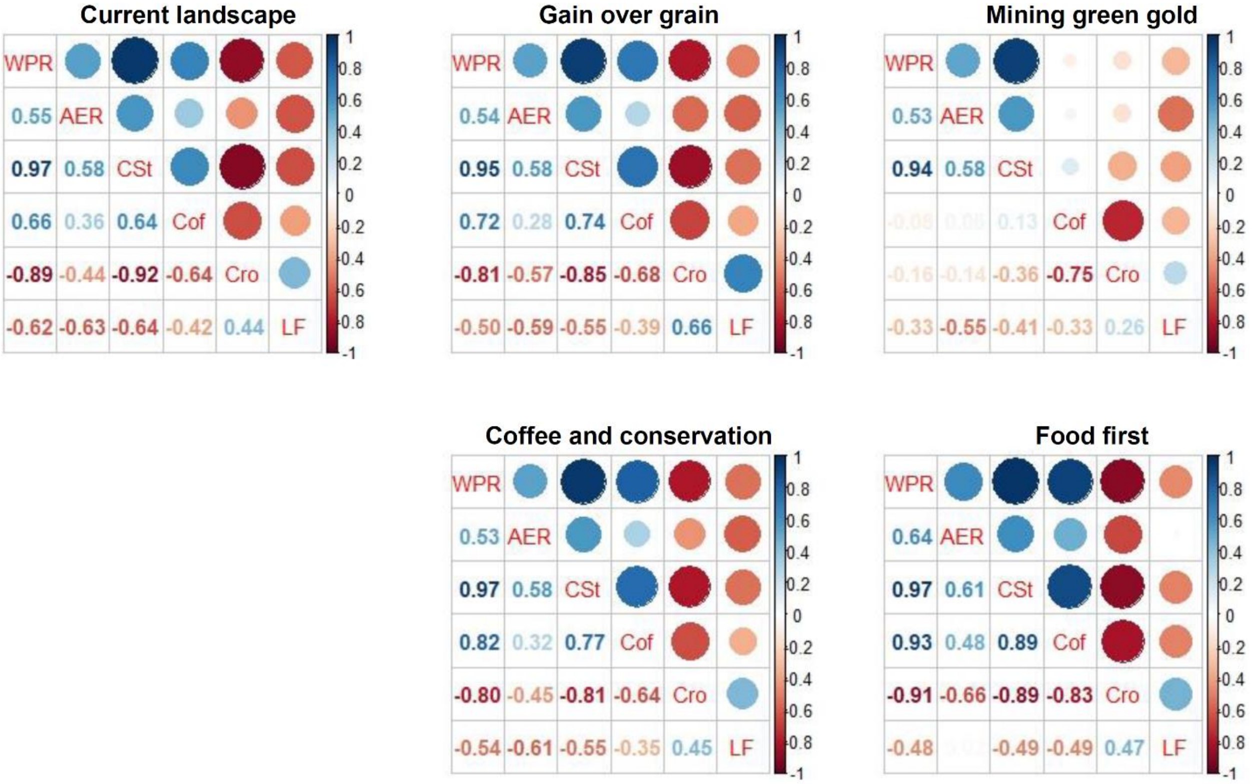

Fig. 3. Correlation analysis showing tradeoffs and synergies between ES under the current landscape and scenarios. (Abbreviations: WPR = Woody-plant richness, AER = Avoided erosion, CSt = Carbon storage, Cof = Coffee production, Cro = Crop production, and LF = Livestock feed). Blues in the graph indicate 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. 2014b; 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 2018b). 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 wellbeing 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 well-being.

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.

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Supplementary materials

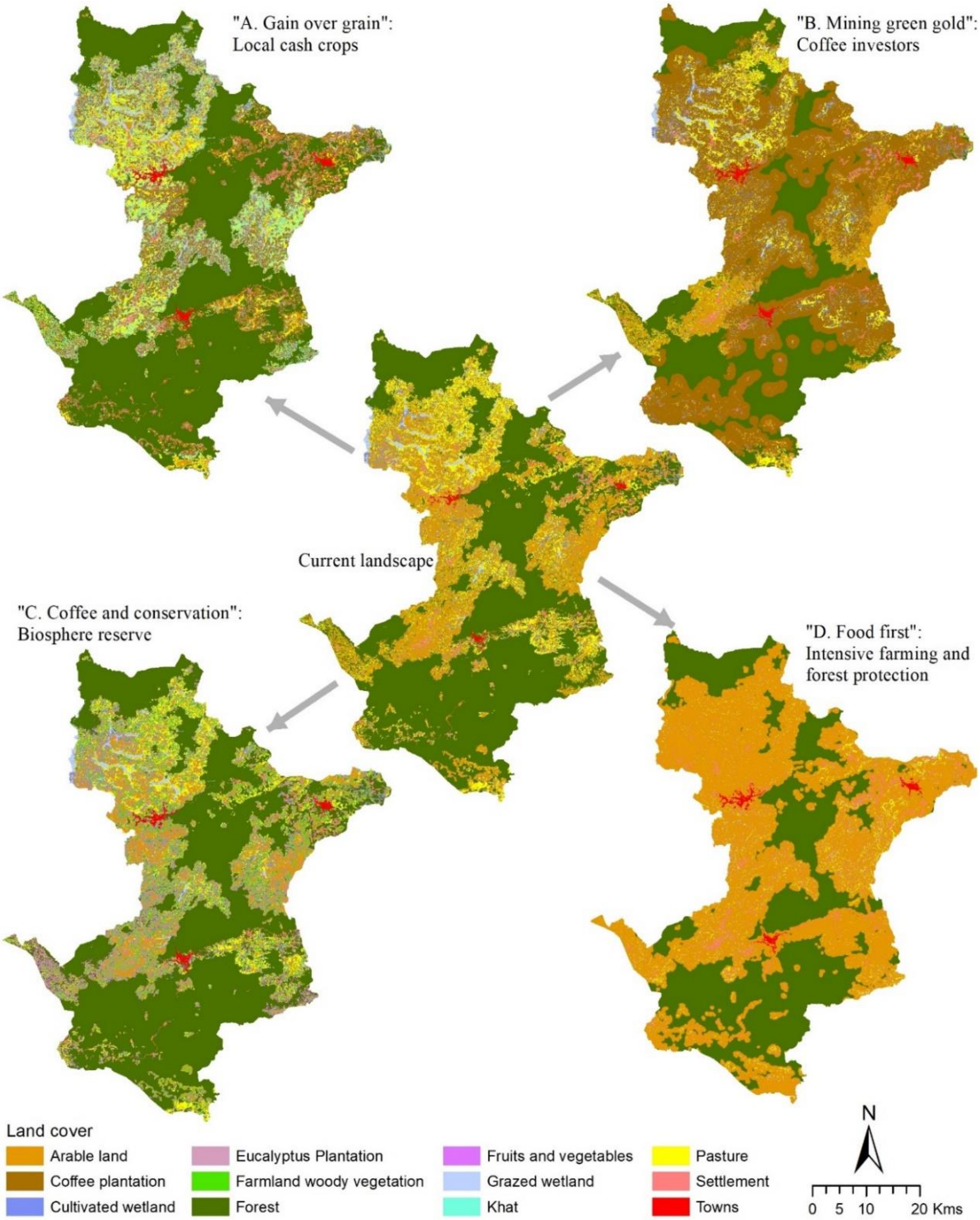

Fig. S1. LULC map of the current landscape and land-use scenarios (reproduced from Duguma et al. 2022).

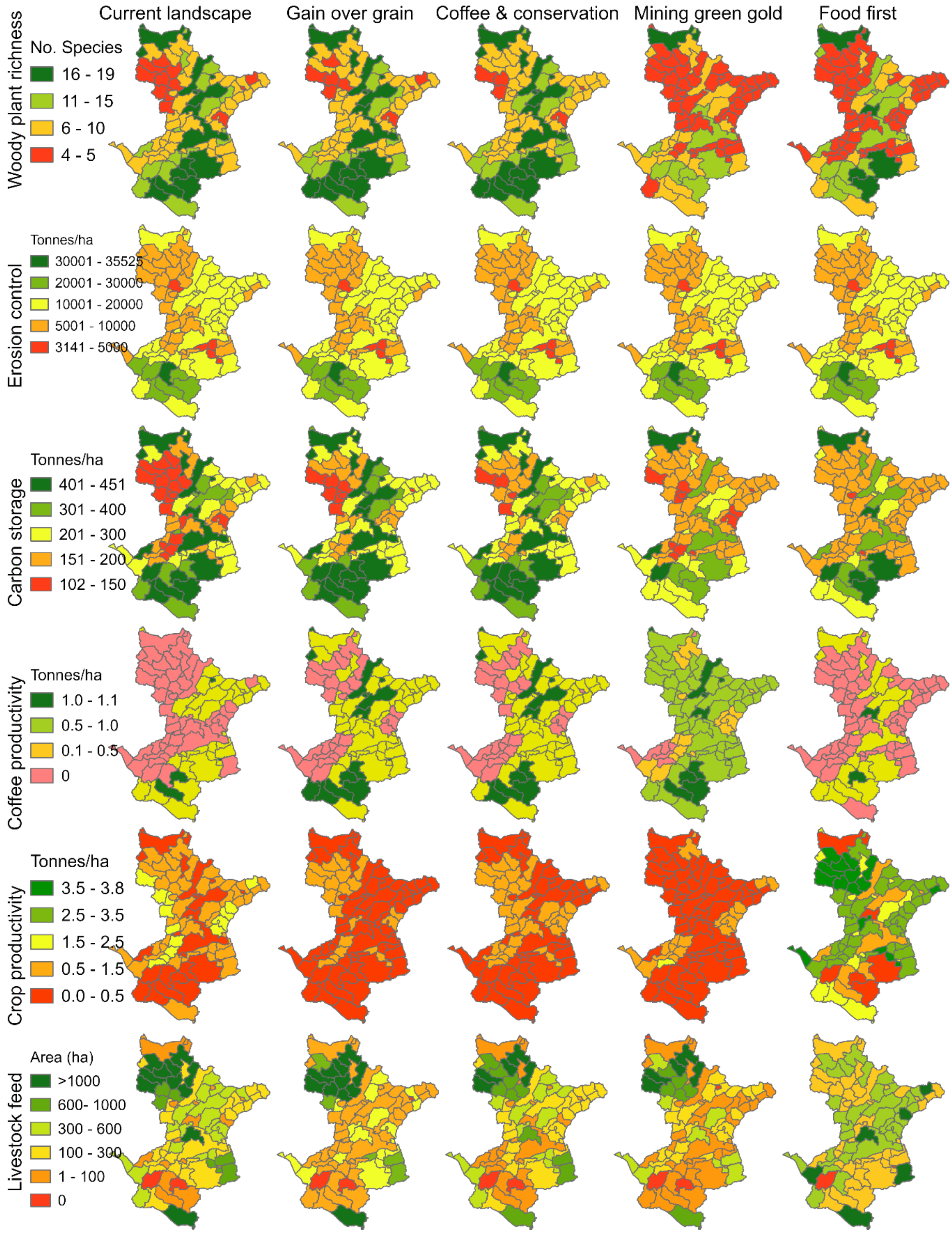

Fig. S2. Absolute values of potential ES for the current landscape and land-use scenarios. Class boundaries were defined using manual classification for visualization purposes and for comparison across the scenarios for individual potential ES.

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 s**upport 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)