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A coffee corridor for biodiversity and livelihoods: climatic feasibility of shade coffee cultivation in western Rwanda

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ABSTRACT

Around the world, restoration activities are underway to halt and reverse ecosystem degradation. A key challenge is to identify restoration approaches that work for both people and nature – i.e. approaches that can sustain livelihoods as well as biodiversity. Here, we focused on a mosaic landscape in western Rwanda. The landscape features two strictly protected remnant patches of Afromontane rainforest (Gishwati and Mukura forests), which are of high conservation value, but are isolated from one another by some 30 km of smallholder farmland. Connecting Gishwati and Mukura forests would be valuable from a biodiversity perspective, but to date, it is unclear how this could be done in a way that is consistent with local people's livelihoods. To that end, we modelled the climatic suitability for growing shade coffee in the area between Gishwati and Mukura forests. We systematically evaluated plausible scenarios of future climate change and found that much of the study area is already suitable for growing coffee, and will become increasingly suitable in the future. In addition, we identified a series of local species that could be used as shade trees. With the study area becoming increasingly suitable for growing coffee over the coming decades, and with suitable shade trees being native to the study area, we argue there is high potential for establishing a shade coffee corridor between Gishwati and Mukura forests. Such a corridor, in turn, could provide a win-win opportunity for biodiversity conservation and local people's livelihoods.

1. Introduction

Many tropical and subtropical landscapes around the world face the challenge of harmonizing biodiversity conservation and livelihood security (Wittman et al., 2017; Kremen and Merenlender 2018; Fischer et al., 2021; Jiren et al., 2021). In such landscapes, local communities often depend on ecosystems to fulfil their basic human needs (Fedele et al., 2021). The resulting pressure on natural resources can cause the degradation of ecosystems (Jayathilake et al., 2021), and thereby threaten both biodiversity and human well-being. Because high levels of human pressure often coincide with historically high levels of biodiversity, many landscapes in the tropics and subtropics are recognized as 'biodiversity hotspots' (Myers et al., 2000; Maxwell et al., 2020). Ecosystem restoration can play an important role in such hotspots: in trying to balance ecological, social, and economic priorities, restoration efforts can lead to a diverse mosaic of different land uses that can, in principle, benefit both people and ecosystems (Di Sacco et al., 2021; Martin et al., 2022).

One example of a biodiversity hotspot that is targeted for mosaic restoration is the landscape surrounding Gishwati-Mukura National Park in western Rwanda. Historically, biodiversity-rich Gishwati and Mukura forests were connected as part of a larger Afromontane rainforest complex extending towards the Congo and Burundi (Kindt et al., 2014). Over the past decades, conflicts and land-use changes caused severe deforestation (Ordway, 2015; Arakwiye et al., 2021). Today, the landscape is heavily degraded, and the Gishwati-Mukura National Park established in 2015 currently consists of two separated forest patches. Local communities living around the protected forest patches heavily depend on small-scale agriculture and often face livelihood insecurity (Clay, 2019; Uwemeye et al., 2020). In response to environmental

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degradation, the last decade has seen many restoration projects, often with a focus on agroforestry and tree plantations (Nash et al., 2020). Although the importance of planting diverse native species and involving local communities is increasingly being recognized, many restoration sites to date are dominated by exotic *Eucalyptus* spp. which offer little biodiversity value (Arakwiye et al., 2021; Mukuralinda and Ntawuhiganayo, 2024), and limited livelihood benefits (Uwemeye et al., 2020). A recent study showed that combining native and exotic species increased the abundance of birds and insects in the region compared to plantations with only exotic species (Mukuralinda & Ntawuhiganayo 2024).

Against this background, shade coffee production of *Coffea arabica* could be an additional avenue to secure livelihoods and at the same time contribute to biodiversity conservation by increasing the connectivity between the two forest patches constituting Gishwati-Mukura National Park. Shade coffee production with native canopy trees can entail numerous ecological and socio-economic benefits. In its native range in Ethiopia, also naturally dominated by Afromontane rainforest, shade coffee sites can harbor high levels of biodiversity (Hylander et al., 2024), provide numerous ecosystem services (Shumi et al., 2020), and contribute to income diversification (Manlosa et al., 2019). Despite differences to Ethiopia – where coffee is a native species and plays a central role culturally – at least some of the benefits of coffee cultivation could also be harnessed in western Rwanda. Especially against the background of population increase, land pressure, and poverty in the landscape surrounding Gishwati-Mukura National Park, coffee farms could be entry-points for integrating a diversity of trees (Vaast and Somarriba, 2014) for biodiversity, food security, and energy security (Mukuralinda et al., 2016).

Historically, *Coffea arabica* production has been restricted to intermediate altitudes at a latitude between 22° N and 26° S (Obso, 2006). Under a changing climate, however, suitable altitudes are expected to shift upwards, enabling production in locations that were previously too cold (Pham et al., 2019; Hylander et al., 2024). Such an upward shift in coffee cultivation suitability could also apply to the Gishwati-Mukura landscape. Although substantial warming is likely in the coming decades, previous assessments of Rwanda's climatic suitability for coffee cultivation (e.g., Nzeyimana et al., 2014; Mukashema et al., 2016) have not considered future climate scenarios.

In this paper, we (i) assess to what extent shade coffee cultivation is currently climatically feasible between the two disconnected forest patches constituting Gishwati-Mukura National Park, (ii) evaluate how climate change might impact this suitability, considering four socio-economic and emission scenarios and two timeframes (2021–2040, 2041–2060), and (iii) identify native tree species suitable for shade coffee production in western Rwanda. Our findings highlight that climatic conditions will become increasingly suitable for growing shade coffee, and that several native tree species could be used to provide a biodiversity-friendly overstorey.

2. Methods

2.1. Study area

We focused on the landscape surrounding Gishwati-Mukura National Park in western Rwanda (Figs. 1, 2), which is part of the Congo-Nile Divide in the Albertine Rift and one of Africa's most biodiverse ecoregions (Bucyensenge, 2018; Plumptre et al., 2021). The landscape ranges from 1350 to 3000 m a.s.l. and features smallholder farmland, tea monocultures, and *Eucalyptus* and *Pinus* spp. plantations (Ordway, 2015). Gishwati and Mukura forests are located approximately 30 km from one another, and both have been subject to severe deforestation, especially during the genocide against the Tutsi and its aftermath (Kanyamibwa, 1998; Ordway, 2015; Arakwiye et al., 2021). By 2002, the core of Gishwati forest had been reduced to 6 km^2 from 700 km^2 in the 1930s (RDB, 2017). Today, both remaining forest patches are very small (Gishwati 15.70 km^2, Mukura 19.88 km^2, (RDB, 2017)), making them vulnerable to fragmentation and edge effects (Haddad et al., 2015). An ecologically effective corridor to link the two patches would be highly valuable from a biodiversity perspective – but would only be viable if it can also generate livelihood opportunities.

For several decades, *Coffea arabica* cultivation has been promoted by the Rwandan government to alleviate poverty (Guarisoet al., 2012), for example in the Lake Kivu region (1500 - 1800m a.s.l.) which borders our study area (Pinard et al., 2014). The general global trend towards simplified sun-grown coffee monocultures rather than biodiverse shade coffee systems (Pham et al., 2019) is also evident in Rwanda, where recent policies promote maximizing coffee yields through increased fertilizer and pesticide use (NAEB, 2024). However, research in the Lake Kivu region showed that mature shade trees were beneficial for *Coffea arabica* production and increased yield by 55 % compared to sun-grown coffee (Pinard et al., 2014). In addition, research from around the world

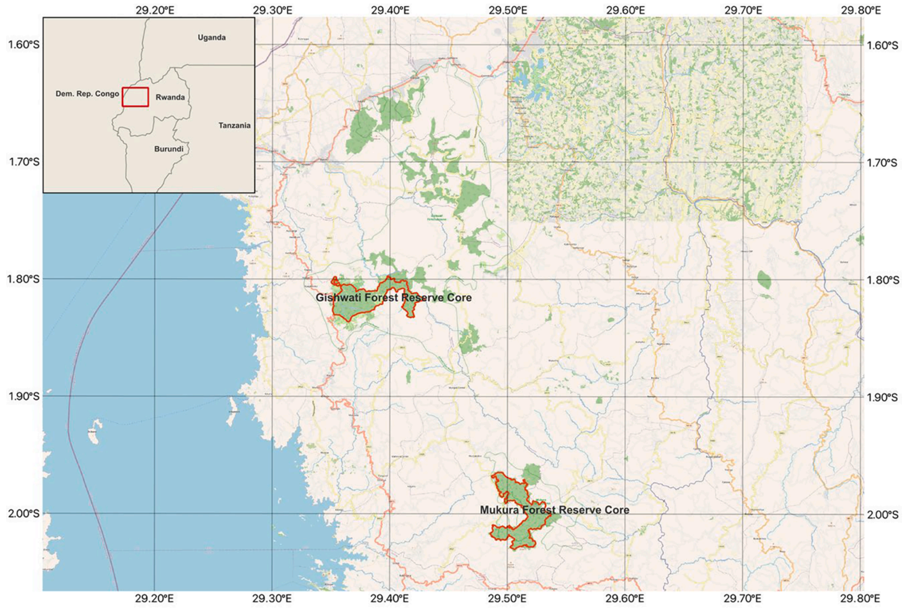

Fig. 1. Study area in western Rwanda. Underlying Map: OSM.

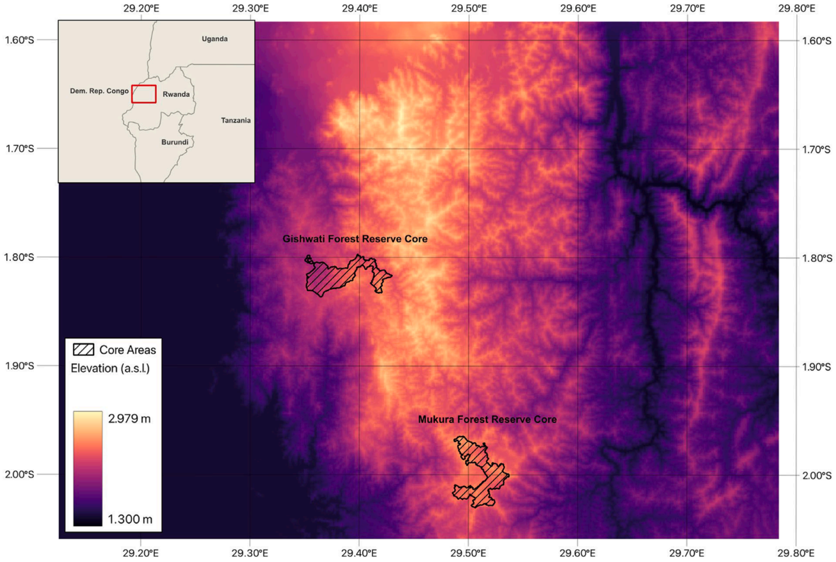

Fig. 2. Elevation profile of the study area in western Rwanda.

shows that shade coffee does not necessarily result in lower yields than sun-grown coffee and can even exceed yields of sun-grown coffee (Haggar et al., 2021; Koutouleas et al., 2022a; Mokondoko et al., 2022).

In Rwanda, an estimated 335,000 – 500,000 households produce coffee as part of their livelihood portfolio (NAEB, 2016; Hakorimana and Akçaöz, 2017). Coffee farms are characterized by small, scattered plots and 56 % of farms have at least some shade trees. On average, farmers dedicate 0.26 hectares of their land to coffee cultivation and often intercrop coffee plots to increase income and food security (Nduwamungu et al., 2025). In general, despite the increasingly important role coffee plays in Rwanda's economy by contributing to foreign exchange earnings and the monetization of the rural economy, yields remain comparably low (0.61 t/ha) (Ngarukiye et al., 2023). With an average of 44.5 % share of total income, coffee is an important part of total household income for farmers. Smallholder coffee farmers invest their own labor due to a lack of other resources (land, outside labor, cash, training) and are the least profitable coffee farms in Rwanda, with larger farms returning up to twice as much gross margin per tree (Clay et al., 2018). Nevertheless, coffee production remains a necessity for smallholder farmers: Clay et al., (2018) describe how Rwandan smallholders use their coffee revenues to meet their most basic needs.

2.2. Data analysis and interpretation

To assess the climatic feasibility of shade coffee production, we carried out a multi-criteria analysis for coffee suitability under the current climate as well as for four future climate scenarios based on a General Circulation Model at two points in the future. We then performed a sensitivity analysis to assess the relationship between model inputs and outputs.

2.2.1. Multi-criteria suitability analysis for coffee

We considered five bioclimatic variables (Bio) that are widely agreed upon to influence conditions for coffee cultivation (Verdoodt and Van Ranst, 2003; Descroix and Snoeck, 2004): *mean annual temperature* (Bio 1), *diurnal range* (Bio 2, i.e., the difference between the daytime and nighttime temperature at a given location), *maximum temperature of warmest month* (Bio 5), *minimum temperature of coldest month* (Bio 6), and *annual precipitation* (Bio 12). These were derived from the openly available WorldClim dataset (WorldClim, 2024a) and were already downscaled and interpolated to a 1 km^2 grid size (Fick and Hijmans, 2017; WorldClim, 2024b).

For the analysis of baseline climatic conditions, we used climate data from 1970–2000. For future projections, we used climate data from NASA's Goddard Institute for Space Studies climate model E2.1-G, for two time spans (2021–2040 and 2041–2060). Both datasets had a spatial resolution of 30 ′. Since it remains unclear to what extent global warming can be limited (IPCC, 2023), we considered four plausible scenarios of societal development in reaction to climate change using Shared Socio-Economic Pathways ((SSPs); see Table 1) (Riahi et al., 2017; IPCC, 2023). Finally, to investigate the relationship between elevation and coffee suitability, a Digital Elevation Model (DEM) of Rwanda with a spatial resolution of 90 m was used (Jarvis et al. 2008).

Data analysis and mapping was performed in QGIS (3.34.5) and R. First, the five bioclimatic variables were extracted from the WorldClim dataset as raster layers and fitted to our study area (i.e., the area between Gishwati and Mukura forest patches and the immediate surroundings). These bioclimatic raster layers were then (i) individually reclassified into five broad suitability classes following Descroix & Snoeck (2004, chapter 6) and (ii) assigned scores on a linear scale from 0 (unsuitable) to 1 (very suitable) (Table 2). As a result of this first step of analysis, we excluded diurnal range from further analyses, because this variable was deemed suitable across the entire area of interest under all scenarios.

We then combined the four remaining raster layers using the Weighted Linear Combination algorithm (Malczewski and Rinner, 2015). Each variable received the same weighting factor of 0.25, resulting in a single multi-criteria suitability layer, which again was scored from 0 (unsuitable) to 1 (very suitable). This process was

Table 1
Shared Socio-Economic Pathways scenarios adapted from IPCC (2023)[1]. SSP = Shared Socio-Economic Pathway.

Scenario	Category Description	Global Warming
SSP 1 - 2.6	emissions decline, 2070 climate neutral	limited to 2 °C
SSP 2 - 4.5	emissions remain the same as current until approximately 2050, then declining	limited to 3 °C
SSP 3 - 7.0	emissions double until 2100	limited to 4 °C
SSP 5 - 8.5	emissions Double until 2050	exceeds 4 °C

[1] IPCC (2023) Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Pages 35–115 (H. Lee and J. Romero, editors). IPCC, Geneva, Switzerland.

Table 2
Classification of five bioclimatic variables which influence conditions for coffee cultivation. Bio 1 = mean annual temperature; Bio 2 = diurnal range; Bio 5 = maximum temperature of warmest month; Bio 6 = minimum temperature of the coldest month; Bio 12 = annual precipitation.

Suitability score	Description of suitability score	BIO 1	BIO 2	BIO 5	BIO 6	BIO 12
1	very suitable with no limiting factor	18–20 °C	< 19 °C	25–26 °C	14–15 °C	1400–1800mm
0,75	very suitable with slight limiting factor	16–18 °C, 20–22 °C	–	26–28 °C	10–14 °C	1200–1400 mm 1800–2000mm
0,5	suitable with moderate limiting factors	15–16 °C, 22–24 °C	–	28–30 °C	7–10 °C	1000–1200 mm 2000–2200mm
0,25	marginally suitable with moderate limiting factors	14–15 °C, 24–26 °C	–	30–32 °C	4–7 °C	> 2200mm 800–1000mm
0	potentially unsuitable	< 14 °C, > 26 °C	> 19 °C	> 32 °C	< 4 °C	< 800mm

repeated for all time spans and scenarios. Finally, for the analysis of the relation between altitude and suitability, suitability values were extracted based on the DEM grid for each of the scenarios individually.

2.2.2. *Sensitivity analysis*

In addition to the variables themselves, the weighting of each variable influences the final suitability score of individual pixels (Chen et al., 2010). Therefore, we tested the robustness of our multi-criteria model by performing a sensitivity analysis using a *one at a time* approach (Więckowski and Sałabun, 2023). A *one at a time* sensitivity analysis involves the alteration of the weighting of one variable while the weighting of the other variables remains constant. This procedure is then repeated for every variable (Chen et al., 2010; Pianosi et al., 2016) to assess the influence of input variables on the suitability score. Based on these results, a dimensionless sensitivity index that approximates how much change in suitability scores can be attributed to a change of weighting can be calculated for each raster pixel (Lenhart et al., 2002; Pianosi et al., 2016). Following (Lenhart et al., 2002), we used four sensitivity clusters to analyze the sensitivity of each variable (Table 3). This process was repeated for all time spans and scenarios. Finally, to complement the *one at a time* sensitivity analysis and identify patterns and underlying structures in the data, we performed K-means clustering using SAGA k-means clustering with five clusters for the baseline climatic data (Richards, 2022) (Fig. S1-S7).

2.3. *Suitable tree species*

To provide practical guidance, we compiled a list of tree species suitable for shade coffee farms in the study area. To this end, we analyzed scientific literature (see Table 5) and three databases, namely the *Interactive Suitable Tree Species Selection and Management Tool for East Africa* (Kuria et al., 2017), the *Useful Tropical Plants Database* (Fern, 2024), and the *African Plant Database* (Conservatoire et Jardin botaniques de la Ville de Genève and South African National Biodiversity Institute, Pretoria, 2024).

The selection of tree species was based on three criteria: trees had to (1) occur either natively or potentially in Afromontane rainforest or Lake Victoria rainforest based on the species composition lists from (Kindt et al., 2011) and (Kindt et al., 2014), (2) belong to the medium/high canopy strata, usually reaching around 10 m or taller, and (3) have been reported to be useful in shade coffee cultivation of *Coffea arabica*. In addition, the resulting list was verified and edited by a Rwandan agroforestry expert (AM).

The identification of potentially suitable species followed a systematic approach that included two steps. First, we considered the native habitat of *Coffea arabica* and, based on Friis et al. (2010), extracted all species that naturally grow together with *Coffea arabica*. Then, based on Kindt et al. (2011), we cross-checked and merged the resulting list of species with species that potentially occur in the Rwandan case study area. Second, we also compiled a list of native tree species that are reportedly present in Gishwati-Mukura National Park. To this end, we included data of tree species occurring in Gishwati or Mukura forests based on Kuria et al. (2017) and Hagumubuzima (2019). We then cross-checked which of these species can be potentially used in *Coffea arabica* shade cultivation based on Friis et al. (2010), Kindt et al. (2011), Kindt et al. (2014), and Fern (2024).

Table 3
Sensitivity classes according to Lenhart et al. 2002, p. 647.

Class	Index $\mid I \mid$	Sensitivity
I	$0.00 \leq \mid I \mid < 0.05$	small to negligible
II	$0.05 \leq \mid I \mid < 0.20$	medium
III	$0.20 \leq \mid I \mid < 1.00$	high
IV	$\mid I \mid \geq 1.00$	very high

3. Results

3.1. *Current suitability*

The climatic suitability for the baseline (1970-2000) indicates partly favorable conditions for coffee cultivation (Fig. 3), especially at altitudes between 1750 and 1800 m. With increasing altitude, coffee suitability decreases (Figs. 3, 4). This decrease in suitability was evident especially for the area between Gishwati and Mukura forests, with suitability around Gishwati forest being slightly higher than around Mukura forest. However, with a minimum suitability of 0.625, even these areas show moderate suitability for coffee cultivation under baseline conditions.

3.2. *Future suitability*

Across all SSP scenarios and both time frames, climatic coffee suitability was found to increase compared to the baseline (Figs. 3, 4). The overall area with moderate suitability decreased notably in all scenarios, while suitability at high altitudes increased substantially. For the period 2021–2040, the highest mean suitability was found at elevations between 1900 and 1950 m. For the period 2041–2060, the highest mean suitability was found at elevations between 2000 and 2100 m (Fig. 4).

At lower elevations, suitability decreased in all scenarios (Table 4, Fig. 5). Instead, we found a substantial uphill shift of coffee suitability that further increased with time and intensity of warming. This trend also shows highly favorable conditions for coffee cultivation up to altitudes around 2400–2450 m (suitability > 0.85). This effect was most pronounced for Scenario SSP585 (2041–2060), where mean suitability was still > 0.75 at altitudes as high as 2900–2950 m (Fig. 4). For the period of 2041–2060, scenarios SSP245, SSP370, and SSP585 show a notable decrease in suitability at lower elevations (Table 4). Most locations near and between Gishwati-Mukura National Park had very high suitability for the time span 2041–2060, suggesting climatically nearly perfect coffee growing conditions across all models.

3.3. *Sensitivity analysis*

Our sensitivity analysis revealed robustness of the models against changes in the weighting of individual input variables, particularly in areas where suitability across variables was considered high. In no model did any variable exceed the dimensionless sensitivity index I of $|0.25|$. All models were most sensitive in very high elevation areas, indicating some uncertainty in these regions. However, even at the highest elevations, sensitivity was found to decrease over time in

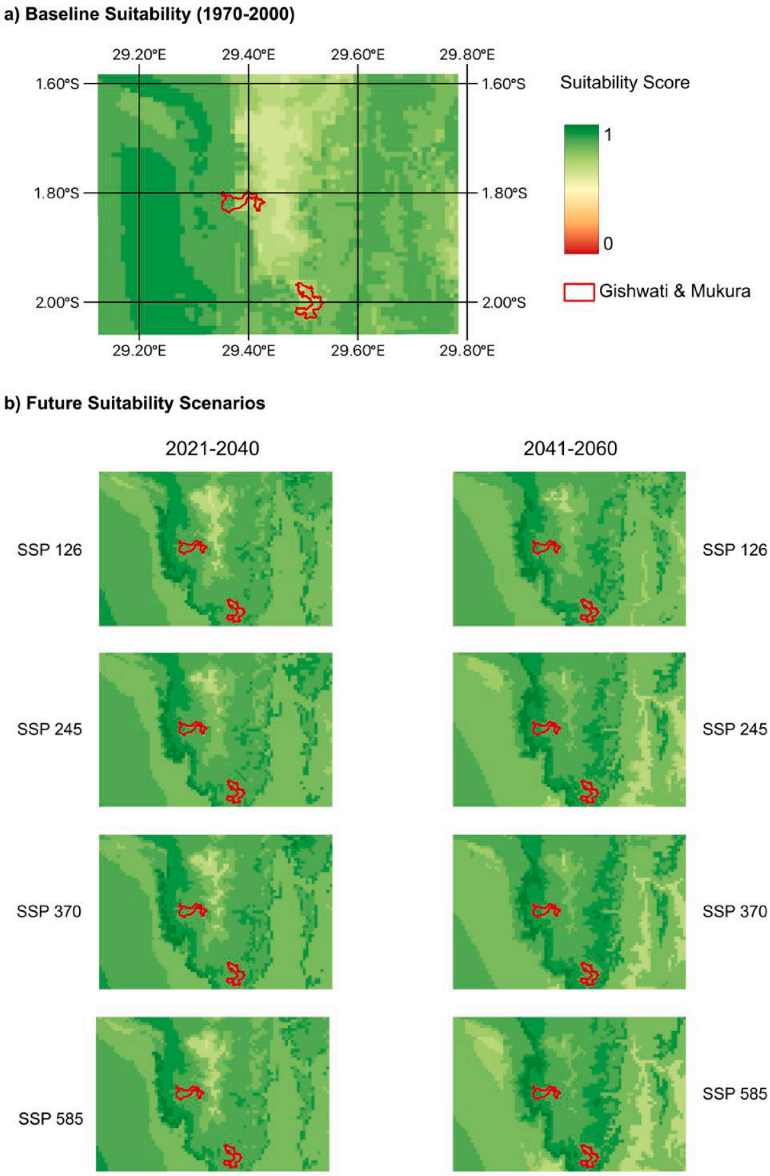

Fig. 3. Coffee suitability score under current climate and suitability score under future climate scenarios, a) Shows the baseline suitability score based on climate data from 1970–2000 b) shows the suitability score based on the eight different scenarios.

equivalent future models (Fig. S2), suggesting that the longer-term future models were more robust to changes in individual variable weightings.

Across all models, *mean annual temperature* showed the highest maximum sensitivity, particularly for high altitude areas. Two variables, namely *maximum temperature of warmest month* and *annual precipitation*, also showed elevated sensitivity at higher altitudes but never exceeding a medium sensitivity index I of $|0.15|$. *Minimum temperature of coldest month* was only slightly sensitive to changes in weighting with I values rarely exceeding $|0.05|$ (Fig. S1, S2).

3.3.1. Bio 1: mean annual temperature

Under baseline climatic conditions, *mean annual temperature* was found to be at the lower boundary of the optimum for coffee cultivation, and in higher altitudes, was below this optimum or even unsuitable. Clustering revealed that cold temperatures at higher altitudes limit coffee suitability (Fig. S3). The sensitivity analysis showed that increasing the weighting of *mean annual temperature* would make temperature a limiting factor at higher altitudes, while decreasing its weighting would reduce this effect. In the future, rising temperatures will mitigate this limitation, often bringing temperatures into the optimal range for coffee cultivation.

3.3.2. Bio 5: maximum temperature of the warmest month

Under baseline climatic conditions, *maximum temperature of the warmest month* was found to be optimal for coffee cultivation for almost the entire study area (Fig. S5). For future scenarios, this variable could, however, become limiting, particularly at low altitudes. Sensitivity analysis revealed sensitivity to *maximum temperature of the warmest month* at high altitude areas. Increasing the weighting of this variable in the baseline suitability model led to increased suitability at high altitudes, while decreasing its weighting decreased suitability. For future models, this effect became smaller.

3.3.3. Bio 6: minimum temperature of coldest month

Under current climatic conditions, *minimum temperature of coldest month* was found to be within the optimal range at low altitudes, but a limiting factor at higher altitudes. Changes in the weighting of this

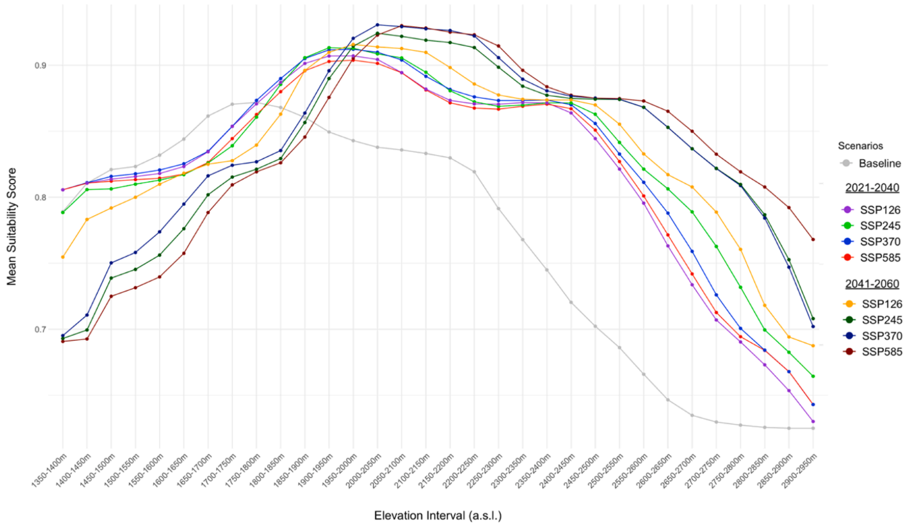

Fig. 4. Mean suitability score by elevation interval across different scenarios and timeframes. The grey line indicates the baseline scenario reference, the other colors show the respective scenario's suitability. Data from Lake Kivu in the western part of the study area was excluded in this graph.

Table 4
Changes in suitability score by scenario and elevation classes based on Duguma et al. (2022). Total Cells refers to the raster cells with a resolution of 1 ′ which corresponds to approximately 1km^2. Increase, Decrease and No change indicate the number of cells.

Scenario	Elevation Class (m)	Total Cells	Increase	Decrease	No change	Percent increase (%)	Percent decrease (%)
SSP126 21–40	1300–1499	117	10	50	57	8.55	42.74
SSP126 21–40	1500–2099	1965	821	617	527	41.78	31.40
SSP126 21–40	2100–2299	524	327	0	197	62.40	0.00
SSP126 21–40	2300+	796	784	0	12	98.49	0.00
SSP126 41–60	1300–1499	117	0	76	41	0.00	64.96
SSP126 41–60	1500–2099	1965	661	827	477	33.64	42.09
SSP126 41–60	2100–2299	524	446	0	78	85.11	0.00
SSP126 41–60	2300+	796	794	0	2	99.75	0.00
SSP245 21–40	1300–1499	117	6	51	60	5.13	43.59
SSP245 21–40	1500–2099	1965	810	739	416	41.22	37.61
SSP245 21–40	2100–2299	524	375	0	149	71.56	0.00
SSP245 21–40	2300+	796	793	0	3	99.62	0.00
SSP245 41–60	1300–1499	117	0	115	2	0.00	98.29
SSP245 41–60	1500–2099	1965	443	1282	240	22.54	65.24
SSP245 41–60	2100–2299	524	523	0	1	99.81	0.00
SSP245 41–60	2300+	796	795	0	1	99.87	0.00
SSP370 21–40	1300–1499	117	10	49	58	8.55	41.88
SSP370 21–40	1500–2099	1965	865	611	489	44.02	31.09
SSP370 21–40	2100–2299	524	372	0	152	70.99	0.00
SSP370 21–40	2300+	796	789	0	7	99.12	0.00
SSP370 41–60	1300–1499	117	0	103	14	0.00	88.03
SSP370 41–60	1500–2099	1965	500	1052	413	25.45	53.54
SSP370 41–60	2100–2299	524	523	0	1	99.81	0.00
SSP370 41–60	2300+	796	795	0	1	99.87	0.00
SSP585 21–40	1300–1499	117	10	50	57	8.55	42.74
SSP585 21–40	1500–2099	1965	785	704	476	39.95	35.83
SSP585 21–40	2100–2299	524	322	0	202	61.45	0.00
SSP585 21–40	2300+	796	788	0	8	98.99	0.00
SSP585 41–60	1300–1499	117	0	115	2	0.00	98.29
SSP585 41–60	1500–2099	1965	385	1288	292	19.59	65.55
SSP585 41–60	2100–2299	524	524	0	0	100.00	0.00
SSP585 41–60	2300+	796	796	0	0	100.00	0.00

variable resulted in very small, negligible changes in overall suitability. As with *mean annual temperature*, rising temperatures will further reduce this effect because colder temperatures become less frequent.

3.3.4. Bio 12: annual precipitation

Increasing the weighting of variable *annual precipitation* raises the overall suitability of the area, as much of the area of interest already receives precipitation within the optimal range for coffee cultivation,

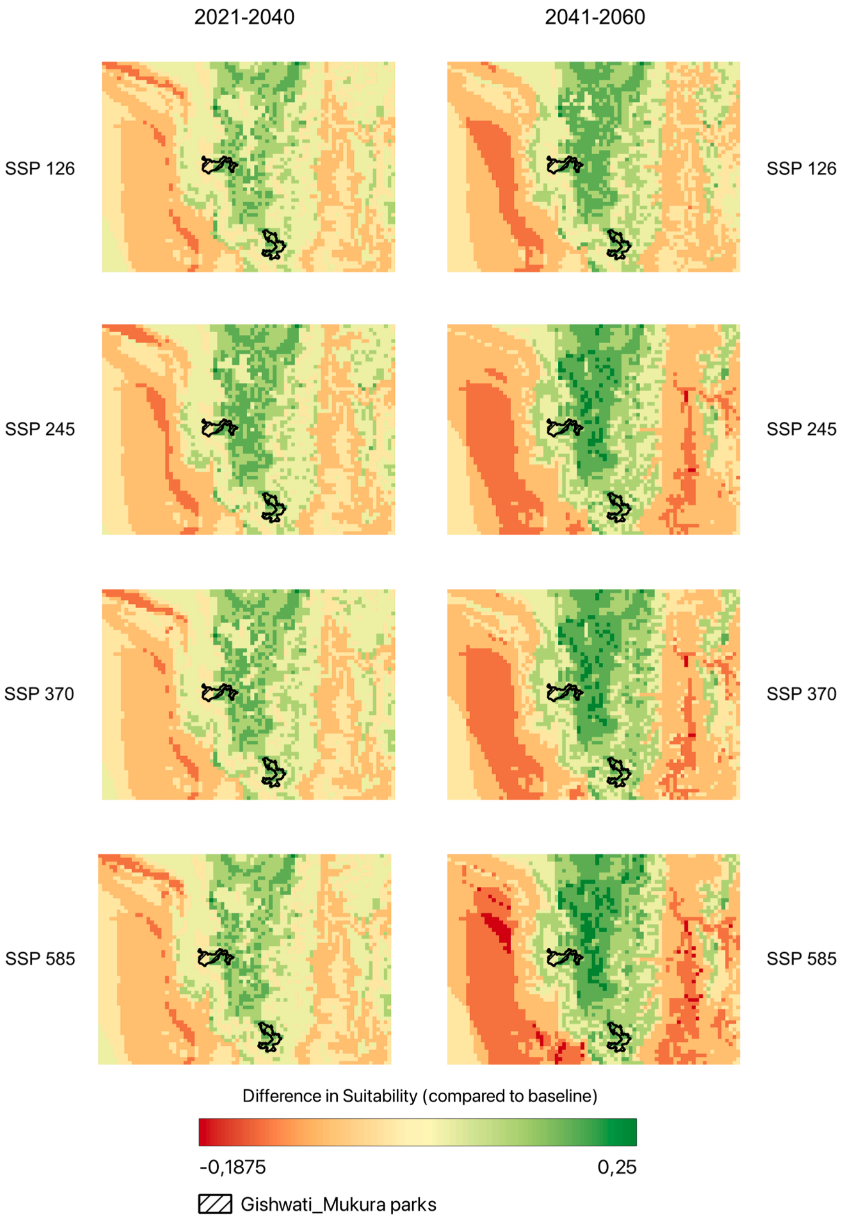

Fig. 5. Difference in suitability score to baseline by scenario. Values between −0.1875 and 0.25 indicate absolute changes. Green coloring indicate increase in suitability, yellow colors show no changes and red coloring hints at a decrease in suitability.

thereby improving overall suitability values. This is especially true in higher elevations, where the comparably lower weighting of other limiting factors leads to increased suitability (Fig. S1, S2). Across future models, precipitation will remain within the optimal range for most parts of the area of interest.

3.4. *Suitable tree species*

In total, 16 tree species were identified as meeting all three selection criteria described in the Methods section (Table 5). Our list of suggested species provides an overview of potential species suitable for shade coffee cultivation of *Coffea arabica*. Local context is a decisive factor in the determination of shade trees' suitability, and local knowledge may ultimately better guide the selection. Future research on additional suitable species would be highly valuable to complement this list. Ideally, this would encompass on-site trials with different species to test their ecological suitability, familiarize farmers with potentially less known species, and evaluate the attitude of farmers to these species. Here, transdisciplinary processes such as a living lab (Hossain et al. 2019) would be best suited to ensure that communities are adequately engaged and, through this, increase community uptake of new knowledge on suitable trees.

4. Discussion

4.1. *Shade coffee cultivation will be increasingly viable*

Overall, our analysis suggests that with climate change, climatic suitability for *Coffea arabica* cultivation in the study area will increasingly shift upwards in the coming decades. As a result, shade coffee production will become increasingly viable in the study area – under all climate scenarios considered, and especially for the high-altitude areas surrounding Gishwati-Mukura National Park. In contrast, in lower altitude areas (1350–1800m a.s.l. for 2021–2040; 1500–1900m a.s.l. for 2041–60; Fig. 4, Table 4), coffee suitability will be impacted negatively by rising temperatures. Our findings align with other studies suggesting

Table 5
Potential shade tree species for *Coffea arabica* cultivation in the study area. GMNP = Gishwati-Mukura National Park.

Tree Species	Canopy Level	Other characteristics	Other Uses[4]	Further Comments
Albizia gummifera[3,4,6,7,9]	20–30 m	nitrogen fixing[10], fast-growing[10], generalist[3]	–	present in Lake Kivu region[6]
Bersama abyssinica[4,8]	10–20 m	forest specialist[3]	firewood, timber, medicine	present in Mukura[1]
Bridelia micrantha[3,4,6]	5–20 m	pioneer[3]	timber	–
Cordia africana[3,4,7,8,9]	10–15 m	generalist[3]	fruits, firewood, timber	–
Croton megalocarpus[4]	10–30 m	pioneer[3]	–	present in Gishwati[1]
Dombeya torrida var. *goetzenii*[3,4]	10–20 m	pioneer[3]	–	present in GMNP[1]
Dracaena steudneri[3]	10–20 m	forest specialist[3]	–	–
Elaeodendron buchananii[3]	10–20 m	generalist[3]	–	–
Entandrophragma excelsum[10]	20–30 m	–	–	present in GMNP[1,2]
Ficus sur[3,4,7]	10–15 m	generalist[3]	fruits, medicine	
Ficus thonningii[3,4,5,6]	10–20 m	generalist[3]	fruits	present in Mukura[1]
Maesa lanceolata[3,4,6]	10–20 m	generalist[3]	firewood, medicine, erosion control	present in GMNP[1]
Markhamia lutea[4,5,6]	10–15 m	fast-growing[10], nitrogen-fixing[10]	firewood, timber, medicine	present in Lake Kivu region[6]
Polyscias fulva[4,5,6]	20–30 m	fast-growing[10], forest specialist[3]	mulch, firewood, timber	present in GMNP[1,2]
Prunus africana[3,4,9]	10–20 m	forest specialist[3]	–	present in GMNP[1,2]
Syzygium guineense[3,4,7,8,9]	10–30 m	forest specialist[3]	fruits, firewood, timber, medicine	present in GMNP[1]

[1] Hagumubuzima 2019.
[2] RDB 2017.
[3] Shumi et al. 2021.
[4] Kuria et al. 2017a & Kuria et al. 2017b.
[5] Smith Dumont et al. 2019.
[6] Pinard et al. 2014.
[7] Ayalew et al. 2022.
[8] Teketay 1991.
[9] Rodrigues et al. 2018;[10]Conservatoire et Jardin botaniques de la Ville de Genéve & South African Biodiversity Institute 2022 & Fern et al. n.d.

that the region near Lake Kivu currently has a high potential for coffee cultivation (Nzeyimana et al., 2014; Bunn et al., 2015; Mukashema et al., 2016).

The overall effect of an uphill-shift in coffee suitability across the global coffee sector will likely also apply to Rwanda. This finding is consistent with several studies predicting a decrease of coffee suitability in low-altitude areas and an increase in high-altitude areas (e.g., Bunn et al., 2015; Chemura et al., 2016; Krishnan, 2017; Moat et al., 2017; Pham et al., 2019; Duguma et al., 2022). In accordance with our findings, increased temperatures, and especially maximum temperatures, are understood to be major drivers of this uphill shift (Chemura et al., 2016). Importantly, in high altitude areas, this climate-induced uphill shift will open up new conservation and cultivation opportunities in locations where shade coffee production was historically not feasible (Pham et al., 2019; Hylander et al., 2024).

4.2. Shade coffee can benefit biodiversity and livelihoods

A shade coffee corridor between Gishwati and Mukura forest patches could be a promising option to reconcile livelihood opportunities and biodiversity conservation in the study area. From a socio-economic perspective, shade coffee patches could be integrated in already existing smallholder agricultural practices (Harelimana et al., 2018; Fischer et al., 2021) and provide smallholders access to resources such as timber, fuelwood, mulch, and medicine (Shumi et al., 2020). Moreover, a prior study on shade coffee in western Rwanda showcased how shade trees positively impact coffee productivity as compared to coffee growing in full sun, making it economically attractive (Pinard et al., 2014).

From an ecological perspective, the potential biodiversity benefits of shade coffee grown under a canopy of native trees could be massive, because at present, native trees remain uncommon in the landscape. Benefits documented elsewhere include increased genetic and species diversity (Perfecto et al., 1996; Jha and Dick, 2008; Krishnan, 2017), habitat provision (Rodrigues et al., 2018), and carbon sequestration (Lugo-Pérez et al., 2023). In addition, through increased soil protection, better water uptake (Pham et al., 2019), and the use of nitrogen-fixing tree species, shade coffee cultivation could help address issues related to bare soils on steep slopes which is related to low soil fertility, erosion, flooding, and landslides (Nzeyimana et al., 2013, 2017).

In terms of connecting the two forest patches that constitute Gishwati-Mukura National Park, shade coffee plots could play a vital role in increasing landscape connectivity and biodiversity on the landscape scale (Mutersbaugh, 2006) by serving as refuge patches, stepping stones or even corridors for diverse species (Mutersbaugh, 2006; Jha and Dick, 2008). Refuge patches are typically small areas where species are shielded from unfavorable conditions (Selwood and Zimmer, 2020) and can be focal points for forest regeneration (Jha and Dick, 2008). Stepping stones act as connectors between habitat patches and can facilitate species' movement through the landscape matrix (Rocha et al., 2021). Ultimately, a fully connected band of coffee forest could constitute a wildlife corridor that would help facilitate the movement of diverse species between the Gishwati and Mukura forest patches.

4.3. Challenges for shade coffee cultivation in the study area

In practice, the expansion of shade coffee in the study area will likely face both social and ecological challenges. First, the selection of suitable and context-appropriate shade trees is critical. For example, some species are highly competitive for water or nutrients during the dry season (Beer et al., 1997; Charbonnier et al., 2013), while other species might provide too dense shade, leading to a decrease in coffee yields (Durand-Bessart et al., 2020). Furthermore, some shade tree species can suppress certain pests and diseases while others can increase their frequency and severity (Bukomeko et al., 2017; Ayalew et al., 2022). Thus, shade tree selection and management are critical components in shade coffee cultivation (see also Recommendations section below).

Second, soil properties, such as soil depth, nutrient content, pH, and soil organic matter strongly influence suitability (Descroix and Snoeck, 2004). In previous studies, the areas close to Gishwati-Mukura National Park were deemed suitable for coffee cultivation in terms of their soil properties (Nzeyimana et al., 2014; Mukashema et al., 2016). In the face of climate change, however, higher amounts of rainfall could result in increased nitrogen-leaching and soil acidity (Chemura et al., 2016) in the already acidic and phosphorus-poor soils in the study area (Nzeyimana et al., 2013). Thus, chemical and physical soil properties in the study area and soil-friendly cultivation practices require further attention to ensure the long-term viability of shade coffee production.

Third, because coffee ultimately would be cultivated by smallholder farmers, their preferences and needs are central for ensuring the adoption and long-term viability of coffee cultivation (Piñeiro et al., 2020). In the study area, land scarcity in combination with widespread direct dependence on land means that household food security is generally prioritized over cash crop cultivation (Mukashema et al., 2016). Hence, coffee cultivation needs to be integrated into already existing livelihood activities in a way that suits people's capacities and needs. Notably, in smallholder contexts such as the study area, shade systems can be a safety net for farmers by generating supplementary income from shade tree products and increasing household's food and nutrition sources (Jemal et al., 2021; Koutouleas et al., 2022b). In this context, native shade trees are reported to be especially valuable due to their multifunctionality (Tscharntke et al., 2011; Nath et al., 2016).

Fourth, to benefit from coffee cultivation, farmers rely on adequate infrastructure, access to (international) markets, and supportive laws and regulations. Coffee washing stations, for example, are vital infrastructure. The Rwandan government supported their development (Mukashema et al., 2016), and our findings show that locations suitable for coffee cultivation coincide with existing coffee washing stations. However, many of these stations have been reported to be not well-managed or even dysfunctional (Guarisoet al., 2012). Another important component of coffee infrastructure is access to roads (Mukashema et al., 2016). Infrastructural conditions thus also need to be assessed carefully to understand which aspects require improvement if shade coffee cultivation were to be expanded.

5. Recommendations

Our findings suggest that a shade coffee corridor between Gishwati and Mukura forest patches could reconcile livelihood security and biodiversity conservation. In practice, the success of coffee agroforestry systems depends on local management practices (Lamond et al., 2019). In southern Mexico for example, certified organic coffee producers formed a network of shade coffee patches that enhanced biodiversity. Coffee certification schemes were crucial for this success (Mutersbaugh, 2006) and could be useful in Rwanda, which already considers certification schemes in its Green Growth and Climate Resilience Strategy (Republic of Rwanda, 2022). A recent study revealed significant positive synergies between biodiversity, livelihoods, and gender equality for coffee systems that adopt voluntary sustainability standards in Rwanda (Wollni et al., 2025). Importantly, in the Mexican example, ineffective communication, insufficient participation opportunities, and inequitable benefit sharing reduced farmers' commitment to organic production and resulted in decreased ecological success and social inclusion (Mutersbaugh, 2006). Stakeholders in the Rwandan context can learn from these challenges. Establishing a coffee corridor in Rwanda should prioritize recognizing local communities' needs and knowledge through participatory frameworks and implementing equitable benefit-sharing mechanisms (Smith Dumont et al., 2018; Zerga and Tsegaye, 2020).

As a practical starting point, our list of potentially suitable native tree species for shade coffee cultivation (Table 5) offers tangible guidance for implementing the proposed approach. By considering and integrating these and other species into their livelihood portfolio, smallholder farmers could benefit from diversified income sources and increased resilience to climate impacts, while potentially also contributing to national biodiversity and conservation goals. Finally, when setting up new shade coffee plantations, practitioners and policy makers can learn from existing afforestation initiatives in the area that have integrated native tree species, such as the LAFREC Project near Gishwati-Mukura National Park (Bucyensenge, 2018). With climate change being inevitable and restoration being a high priority for the Rwandan government, the coffee corridor proposed in this paper should be carefully considered as a possible win-win for people and ecosystems.

CRediT authorship contribution statement

Tom Reckmann: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Marina Frietsch:** Writing – review & editing. **Christoph Schwenck:** Writing – review & editing, Visualization, Supervision, Methodology, Formal analysis. **Athanase Mukuralinda:** Writing – review & editing, Validation. **Dula Wakassa Duguma:** Writing – review & editing, Methodology, Formal analysis. **Joern Fischer:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

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

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Supplementary materials

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Data availability

The data hat has been used is freely available online.

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