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Views from two mountains: exploring climate change impacts on traditional farming communities of Eastern Africa highlands through participatory scenarios

Running title: Participatory scenarios in Eastern Africa highlands

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Abstract

African mountains are characterized by high levels of biodiversity and provide ecosystem services to millions of people. Due to steep environmental gradients, growing human populations and geographical isolation, these coupled socio-ecological systems are highly vulnerable to climate change impacts. The capacity of local stakeholders to anticipate future changes and to assess their potential impacts are paramount for enhancing adaptation and resilience. Here we apply a participatory scenario development framework in two parts of the Eastern Afromontane Biodiversity Hotspot: Taita Hills in Kenya and Jimma rural area in Ethiopia. In each area, we facilitated local stakeholders in envisioning adaptation scenarios under projected climate changes by mid-21st century, and assessed the potential impacts of these pathways on land use and land cover. In the Taita Hills, under a business-as-usual scenario, human population and activities concentrate at high elevation, triggering cascade effects on remnant forest cover, biodiversity and ecosystem services. Alternative adaptation scenarios envisage reforestation associated with either improved agricultural practices or ecosystem restoration. In the Jimma area, rising temperatures are expected to disrupt traditional coffee production under a business-as-usual scenario, resulting in the loss of coffee-forest canopies and reduction of forest-dependent biodiversity. Alternative adaptation scenarios envisage either expansion of commercial coffee plantations or expansion of agroforestry, including traditional coffee farming. In the both Taita and Jimma, adaptation pathways present trade-offs between provisioning, supporting and regulating services, and between livelihoods and biodiversity conservation. Our findings encourage the use of multidisciplinary, bottom-up approaches for developing locally tailored, climate-smart and sustainable adaptation pathways.

Key words: adaptation, sustainable development goals, land changes, agroforestry,
coffee farming, resilience

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Introduction

Along with population growth (Canning et al. 2015) and anthropogenic land use and land cover changes (Brink et al. 2014, Schmitz et al. 2014), climate change is amongst the greatest future challenges for many African countries (Niang et al. 2014, Gasparatos et al. 2016). Tackling climate change then will have substantial influence on the achievement of sustainable development goals (SDGs), at country and local levels, such as poverty reduction, food security, and ecosystems conservation and restoration (Fleurbaey et al. 2014, 2030 Agenda for Sustainable Development).

In mountain areas, the steep climatic gradients and scarcity of observation make it difficult to assess and model potential climate change impacts at local scale, and therefore to plan adaptation strategies. These adaptation strategies require a holistic approach explicitly addressing non-climatic factors (Räsänen et al. 2016), including common montane traits such as geographical isolation and remoteness and adaptive responses to altitudinal gradient which increase either vulnerability or resilience to climate. East African mountain ecosystems are highly productive agricultural areas supporting large populations that have experienced intense migration flows and extensive land cover changes over the last century (Marchant et al. 2018). In montane areas of Ethiopia and Kenya, projected climate change by the mid-21st century is characterised by an increase of temperature, increased frequency of extreme events, and uncertainty of precipitation patterns; wetter rainy seasons are expected in Kenya and prolonged aridity in Ethiopian highlands (Platts et al. 2015). Temperature increases could benefit maize and bean production at high elevation (Adhikari et al. 2015), thereby implying a potential shift upwards of maize farming but also potential land use conflicts. However, climate change effects are likely to extend to pest–host interactions and plant defence mechanisms which ultimately affect crop suitability (Calatayud et al.

2016, Ntiri et al. 2016, Ngowi et al. 2017). Globally suitable agro-climatic zones for growing *Coffea arabica* are expected to significantly diminish, although increased temperature could favour its production at higher elevation and close to the Equator (Ovalle-Rivera et al. 2015). With higher temperatures increased potential damage by coffee berry borer *Hypothenemus hampei* (Jaramillo et al. 2011) and coffee leaf rust *Hemileia vastatrix* disease (Toniutti et al. 2017) are expected.

In such uncertain and complex picture, understanding how local stakeholders can respond to future changes, and building their capacity of anticipating potential impacts of alternative adaptation strategies on ecosystem services, biodiversity and livelihoods are paramount for enhancing adaptation and social-ecological system resilience.

Scenario analysis can contribute to these objectives and has been applied in a wide range of studies to address environmental and sustainability problems (Kishita et al. 2016). In the climate change context, scenarios respond to the needs of addressing knowledge gaps in potential future vulnerability and acquired resilience, and to inform decision-making on potential trade-offs between goals and expectations (e.g. maladaptation) (McDowell et al. 2016). By addressing multiple dimensions, scenarios can integrate projected climate change impacts (outcome vulnerability) with socio-economic and environmental trajectories (context vulnerability) (O'Brien et al. 2007, Joakim et al. 2015). The scenario framework offers the opportunity to tackle climate change adaptation pathways by engaging multiple stakeholders (Jurgilevich et al. 2017) and by exploring potential positive opportunities deriving from changes (McDowell et al. 2016). Stakeholders' engagement brings the mediating effect of indigenous knowledge, response to local climate effects (Savo et al. 2016), and the potential barriers of community capacity and willingness to adapt. The use of participatory, place-based and bottom-up scenarios frameworks for biodiversity and ecosystem services

assessment within landscapes is highly recommended, though still limited (IPBES 2016, Kok et al. 2017). Furthermore, holistic scenarios integrating different challenges such as climate changes and land use and land cover changes are lacking (Kishita et al. 2016). In this study, we apply a participatory scenario modelling framework (Capitani et al. 2016) to assess potential societal responses to the impacts of climate change by the mid-21st century, and model consequent land use and land cover change scenarios under different livelihood futures as guided by communities' members in the areas under investigation. We focus our analysis on two montane sites of the Eastern Afromontane Biodiversity Hotspot (Mittermeier et al. 2011), the Taita Hills, Kenya, and a montane area north-west of Jimma, Ethiopia (Fig. 1). In the Taita Hills, communities rely on a variety of staple and cash crops, timber and non-timber forest products, while in the Jimma study area, coffee production is an important income source, coupled with staple food crops production. Beside livelihood strategies, the two study areas differ by timing of deforestation trends (past century *versus* past decades), human population density (high *versus* low) remoteness and isolation degree (higher *versus* lower access to markets and services), rainfall patterns (bimodal *versus* unimodal) and projected changes (increased *versus* decreased rainfall). We present potential adaptation pathways to projected climate changes in these two social-ecological systems and discuss their implications in relation to multiple ecosystem services, and their interactions with SDGs.

Materials and methods

Taita Hills

The Taita Hills study area covers approximately 895 km² ranging between 600 and 2200 meters above sea level (m a.s.l.) in the Taita Taveta County, Kenya (Fig. 1). In

this study we refer to three altitudinal zones in the study area identified in relation to agro-ecological zones and main villages location: low zone (below 1200 m a.s.l.), middle zone (1200-1700 m a.s.l.), and middle-high zone (above 1700 m a.s.l.). The Taita Hills are located at the junction of the main highway between the cities of Nairobi and Mombasa, and the main highway towards the Tanzanian border. In Taita Taveta County, population grew from circa (ca.) 111,000 in 1969 to ca. 285,000 in 2009 and is projected to reach ca. 345,000 by 2017 (KNBS 2009). Accordingly, population density has increased in the Taita Hills, reaching up to 1540 persons/km² in the main villages of the middle zone (KNBS 2009), with consequent agricultural expansion, heavy degradation of the indigenous cloud forests and increased water stress (Maeda et al 2012). Only 1% of the original forest cover remains preserved as scattered cloud forest (Pellikka et al. 2009). Agriculture is the main income source, dominated by maize, horticulture and fruit trees. Livestock keeping is limited to the low zone where off-farm income is mainly related to tourism, transport and mining. In this region, climate is influenced by the Inter-Tropical Convergence Zone (ITCZ) which leads to a bi-modal rainfall pattern, with long rains during March–May/June and short rains in October–December, corresponding to the temperature peak (Clark and Pellikka 2009). Precipitation and temperature vary across the area, influenced by elevation and aspect (Table 1). By the mid-21st century, under Representative Concentration Pathway (RCP) 4.5 scenario (IPCC 2014), mean annual temperature and mean annual rainfall are projected to increase by 1.8 C° and 72 mm/km² yr⁻¹ respectively on average across the study area (AFRICLIM 3.0, Platts et al. 2015, Table 1); increased variability of season onset and duration is also expected, particularly for short rains.

[Figure 1]

Jimma area

The Jimma study area covers a small portion (425 km²) of the Didessa river catchment in southwestern Ethiopia between 1400 and 2400 m a.s.l., in the Jimma administrative zones (Fig. 1). Similar to the Taita Hills, we identified three altitudinal zones in the study area corresponding to agro-ecological and village zones: middle zone (below 1700 m a.s.l.), middle-high zone (1700-2000 m a.s.l.), and high zone (above 2000 m a.s.l.). The area is regarded to be a region of endemic *C. arabica* (Mittermeier et al. 2011). The Jimma administrative zone had an estimated population of ca. 2,487,000 in the 2007 census, increased by 27% over the 1994 census; in the study area, the highest population density was recorded in a census unit of the low zone (204 persons/km², CSA 2007). In the Jimma study area, forest cover dominates the landscape above 1750 m a.s.l. while agriculture has expanded at lower elevation (Hailu et al. 2014, 2015a). Livelihood is mainly based on subsistence agriculture, in particular maize, but organic coffee farming is an important income source. The majority of farmers in the study area collect berries from wild plants in natural forests or from semi-forest coffee systems (Denu et al. 2016), characterized by thinning of canopy trees, removing of ground vegetation and enrichment of empty spaces by transplanting naturally regenerating seedlings of coffee (Teketay 1999).

Deforestation has occurred in the southwestern Ethiopian highlands due to population growth and conversion to farmland in the past decades (Getahun et al. 2013, Hailu et al. 2015a), while many remnant forest patches coincide with suitable areas for coffee farming and, to a lesser extent, sacred forest groves (Denu and Belude 2012).

This part of the country is characterised by a humid subtropical climate influenced by the ITCZ (Table 1). A unimodal rainfall pattern falls between February-May and September, corresponding to the temperature peak. By the mid-21st century, under RCP 4.5 scenario (IPCC 2014), mean annual temperature may increase by 2.3 °C and mean

annual rainfall decrease by ca. 31 mm/km² yr⁻¹ are expected on average across the study area along with increased duration of dry season (Table 1).

[Table 1]

Scenarios development

The scenarios building framework follows a mixed approach (Capitani et al. 2016) whereby local stakeholders develop qualitative and semi-quantitative scenarios guided by a team including facilitators and modellers. The modellers then translate this information into quantitative and spatially-explicit outputs. The final outputs are created following subsequent stakeholders' validation of preliminary results.

In the Taita Hills, we held three multi-stakeholder workshops between February and October 2015. The complex landscape in this area required an additional workshop compared to the framework design to analyse in details potential future land changes and their spatial patterns. Results were validated in a synthesis workshop in September 2016. In the Taita Hills, we engaged 30 participants in scenarios development including 14 farmers, 8 government officers, 2 non-governmental organisations delegates, and 6 members of associations for women and disabled people. The final feedback and validation workshop gathered 21 people, a stratified subsample of the scenario development group including farmers and delegates of local authorities and associations. In the Jimma area, two workshops were conducted in June 2015 and September 2016 and the results were validated in a synthesis workshop in August 2017. In the Jimma area, we engaged 32 participants in scenarios development including 18 local farmers, 10 academics and four local officers. The feedback and validation workshop engaged 24 people including 18 local farmers, five academics and a local officer from the forestry and wildlife office. The scenario development workshops were organized in parallel to the development of the strategic plan for climate change (CC)

adaptation interventions (Owidi et al. 2015a, 2015b), which required participatory mapping of experienced climate- and non-climate driven changes in the area, and identification of high risk areas prioritized for action. A sub-sample of the county-level stakeholder groups targeted by this process was involved in the scenarios development process that was meant to address potential impacts of alternative adaptation pathways over a long term. In both areas, stakeholders' analysis was facilitated by long-term knowledge and research activities of the project partners in the areas. Stakeholders were selected by following the criteria of representativeness of different communities across the elevation gradient and of inclusion of multiple users and managers of land and water resources. Limited evidence of adaptation initiatives targeting socioeconomically disadvantaged or vulnerable community members has been reported (Ford et al. 2015), and therefore we encouraged participation of women and people with some form of disability.

In the initial workshops for scenarios development, participants organised in focus groups discussed land management and climatic variability observed in the past. Then they identified potential socio-economic and environmental trajectories and their drivers under future projected climate conditions and alternative adaptation strategies. In the following workshops, the participants described spatially explicit patterns of expected land use and land cover changes under the different scenarios by defining the likelihood of change (on a 0-4 scale) and biophysical and socio-economic factors influencing it.

Land use and land cover change scenarios were modelled using 100 m-resolution baseline maps obtained resampling high resolution land use and land cover maps for the Taita Hills (Clark and Pellikka et al. 2009, Heikinheimo 2015) and for the Jimma area (Hailu et al. 2014, 2015b). Expected future land use and land cover changes were quantified over a 35-year period, based on past trends for cropland expansion and

deforestation rates from remote sensing analysis (Clark and Pellikka et al. 2009, Heikinheimo 2015 for the Taita Hills; land-cover maps developed at the Regional Centre for Mapping of Resources for Development (RCMRD)/SERVIR-Eastern and Southern Africa for the Jimma area) and on expected scenario trajectories developed during the multi-stakeholder workshops (Supplementary 1a and 1b). Therefore the presented scenarios represent a potential quantification within the range of the envisaged trajectories. The spatial pattern of land use and land cover changes expected by workshops participants were simulated by composite indicators of likelihood of change built from high resolution spatial datasets, including mid-21st century projections temperature and rainfall regime changes derived from AFRICLIM 3.0 (Platts et al. 2015), population distribution (Worldpop, Lloyd et al. 2017), elevation and slope (SRTM 90, Jarvis et al. 2008), rivers and roads extracted from satellite image datasets. In the final validation and feedback workshops stakeholders provided information that was used to refine the scenarios. Furthermore we elicited the participants' reflection on potential impacts on ecosystem services state (e.g. increase, decline, or stable) under the proposed alternative scenarios compared to the current situation.

Results

Taita Hills

In the Taita Hills, under assumptions of increased rainfall and temperature, and increase in seasonal regime variability by mid-21st century, we developed three scenarios (Supplementary 1a): opportunistic coping strategy (business as usual, BAU); integrated adaptation focused on agriculture, the “food production” (FP); integrated adaptation focused on forests and ecosystem services, the “green integration” (GI). Under the BAU scenario individual coping strategies and not-integrated community interventions

persist. Cropland increases by 5% at expense of woodland, thicket and forest (-13%, -6% and -21%, respectively, Table 2), despite ban on logging. Cropland expansion is expected in the middle and middle-high zones, driven by productivity decrease, increased crop suitability at higher altitudes and increased demand (Fig. 2b-e). Demand for more cropland for ensuring staple food production follows the decline of soil fertility and land productivity, and changes in agro-ecological zones. Abandoned farmland is encroached by shrubs and built-up areas. Degradation of wooded land leads to an increase of shrub lands in the low zone. Forest plantation cover increases by 18% replacing cropland and woodland.

[Table 2]

In the Taita Hills adaptation scenarios, new land is converted into agriculture despite of changed climate conditions because of increased availability of water in these areas (following better land management and water harvesting infrastructure), improved water utilisation (e.g. drip irrigation), and increased use of drought resistant crops (Table S1.1). The food production scenario entails a modernisation of the traditional livelihood systems through improved agronomy practice and capacity. The agricultural mosaic landscape is maintained and expands (+16%, Table 2), forest cover increases by 27%, mainly in the middle-high zone (Fig. 2c-e). In the green integration scenario, most effort is directed to increasing indigenous forest cover (+90%, Table 2), even by replacing exotic species, to improve water retention, regulation and purification, and humidity absorption in the hills. Income generating activities that are increasingly focused on the low zone result in partial re-naturalisation of the landscape in the middle and middle-high zones (Fig. 2d-e). In the both adaptation scenarios, infrastructures, particularly the road network, are improved.

[Figure 2]

Jimma area

In the Jimma study area, under the assumptions of increased temperature, slightly higher aridity and seasonal regime variability by mid-21st century, we developed three scenarios (Supplementary 1b): adaptation efforts are failing on the long term because of low uptake by farmers (business as usual, BAU); adaptation is sustained by coffee industry expansion (CI); and adaptation is sustained by agroforestry expansion (AGF). In this study area, stakeholders proposed to include new land use and land cover classes in the mid-21st century scenario maps, such as degraded land, commercial coffee plantations and agroforestry (Fig. 3). In the BAU scenario, climate change effects push a shift from traditional coffee farming and other cash crops (fruit trees and horticulture) to arable cropland for stable food production, with consequent high deforestation rate (-40% forest cover, Table 3). Stakeholders expected conversion of forest and cropland into degraded land and further expansion of exotic trees. Small-scale highly managed coffee plantations are established in the middle-high and high zones (Fig. 3b-e), to improve coffee production compared to wild and semi-managed coffee growing in the face of higher temperatures and increased disease incidence.

[Table 3]

In the Jimma adaptation scenarios, adaptation is implemented through improved agricultural practices and adequate technology, particularly the use of disease resistant coffee seeds, old plants replacement and planting of shade trees; in addition, investment in social services and infrastructure enhance capacity building and access to credit (Table S1.2). This leads to decreased deforestation rates (-6% forest cover, Table 3). In the coffee industry scenario, the cost of this transformative adaptation is taken over by commercial farms, along with coffee production. Coffee is almost exclusively produced in shaded but highly managed coffee plantations that expand into areas that have

become suitable for coffee production (e.g. near the rivers and at higher elevation than in the baseline, Fig. 3c). This scenario implies a shift for local farmers from independent producers to farm workers or out-growers. In the AGF scenario, agroforestry expands over semi-opened forest patches, and across forest-cropland edges (Fig. 3d).

Deforestation rate is low, and opened forest is managed for agroforestry. This system allows for production of both staple and cash crops, and sustains the maintenance of traditional semi-managed coffee plantation associated with beehives.

In the Jimma study area, the elevation pattern of land use and land cover changes is similar across the scenarios (Fig. 3e), and foresees an upward shift of land use intensification and forest conversion to farmland, coffee plantations or agroforestry. This pattern reflects population distribution, the altitudinal climate gradient and projected temperature changes expected to largely influence the spatial patterns of land use and land cover change by workshops participants.

[Figure 3]

Qualitative assessment of impacts on biodiversity and ecosystem services

In the both Taita Hills and Jimma, food provision, water regulation and climate regulation were indicated as key ecosystem services by workshops participants. Qualitative assessment of climate and land change scenarios impacts on ecosystem services and biodiversity relative to the baseline produced different outcomes across participants groups (Supplementary 1c). In the Taita Hills, workshop participants consistently expected decline for all services in the business as usual (BAU) scenario compared to the baseline, e.g. “food will be less available due to cropland degradation”. Contrarily, improvement was expected for all services in the green integration scenarios (GI), e.g. “water regulation will improve following reforestation”. For the food production scenario (FP), different groups highlighted different impacts between

cultural/provisioning and regulating/supporting services relative to the current state, e.g. “soil erosion will be better regulated thanks to improved practices” versus “soil erosion will stay similar due to agricultural use” (Fig. S1 a-b). Similarly, in the Jimma study area workshop participants consistently expected that all ecosystem services “will decline” in the business as usual while they “will improve” in the agroforestry scenarios. However, the academics and officer expected better impacts on cultural and provisioning services in the adaptation scenarios than the farmers groups, compared to the baseline (Fig. S1 c-d). Expectations were particularly diverging for provision service in the coffee industry scenario, e.g. “wages will allow to buy more food” according to the academics and officer group, while the farmers group expected “food provision will be the same because some farmers are no longer producing it”. Workshops participants generally expected biodiversity improvement under the adaptations scenarios in the two study areas and its decline under the BAU scenarios. Only the women group in Jimma expected the same biodiversity state in the adaptation scenarios as in the baseline.

Discussion

In this study, we analysed potential adaptation pathways in response to climate change in two different socio-ecological systems of East African mountains, by applying a novel approach for mixed qualitative-quantitative scenarios co-production.

This approach enriched climate scenarios narratives with the local perspectives and allowed integration of local knowledge into quantitative assessments, therefore enhancing participants’ sense of ownership and the outputs relevance. The scenario development and feedback process contributed to building the local stakeholders’ capacity for long-term ecosystem management and climate adaptation. However, participatory scenario development is a highly demanding process, which partly limits

its application. Participatory approaches can be affected by power dynamics that in our study we prevented by encouraging individual participation and creating homogeneous focus groups by gender and social conditions. Additionally, these approaches require adequate communication tools with non-expert audiences. For example, in our study we used local landscapes images along with maps to represent current and scenario conditions.

Stakeholders' perceptions on climate change

Climate change is a long-term phenomenon difficult to detect, but people may shape their perception based on personal experience of increased climate variability (Weber 2016). In the Taita Hills, participants in our study reported increasing frequency and severity of drought and floods, variability of seasons onset, rainfall irregularity and scarcity in the last decade. These local perceptions are not reflected in official meteorological observations, contrarily to what reported for other studies (Savo et al. 2016, Cuni-Sanchez et al. 2018). The discrepancy may be due to inadequate cover of this area by meteorological stations. Furthermore, misperception could derive from misunderstanding of causes and effects (Hitayezu et al. 2017) and from attributing to climate change the severity of impacts influenced even by other factors, such as increased population and inadequate land management practices (Pyhälä et al. 2016). In the Jimma study area, participants in our study reported higher stability of climate conditions over the last decades. However, local communities have recently experienced variability of rainfall spatial distribution, and an increase of disease insurgence threatening coffee production, even at higher elevations. A greater access to meteorological information and as well as greater engagement in strategic planning can enhance awareness on potential climate change impacts and readiness for adaptation (Owidi et al. 2015b).

Business as usual scenarios

In the Taita Hills, agriculture expansion rate has slowed down in the last decade, and shifted to the low zone (Maeda et al. 2012, Heikinheimo 2015). Most land in the middle and middle-high zones is already in use and parcelled in small plots, except the small forest patches hosting endemic and specialist species (Norfolk et al. 2017a). In the business as usual scenario, a concentration of human presence and activities in a relatively small area could trigger a vicious circle of soil degradation and deforestation, and feedback effects on water availability, crop productivity, biodiversity and social conflicts. Higher temperatures contribute to increased growth, survival and reproductive rates of pest insects in the higher altitudes and agro-ecological zones (Mwalusepo et al. 2015), where the crop damages have not been widely experienced earlier.

Contemporarily, higher temperatures enhance Silicon assimilation and pest defences in cereals (Catalyud et al. 2016), thus generating new host-pests interactions that would require adaptation of integrated pest management.

In the Jimma area, higher land availability than in the Taita Hills could actually encourage a great upwards expansion of population and maize production as response to temperature increase, threatening the remaining forest cover. Temperature increase by mid-21st century could intensify coffee diseases incidence (Garedew et al. 2017a) and bring in new pests (Jaramillo et al. 2011), therefore affecting coffee production, and pushing agriculture expansion at higher elevation. Variability of rainfall regime can also influence the coffee berry disease insurgence. Earlier rains onsets can decrease the disease impacts because at the optimal time for the disease infection coffee berry are already grown enough to react; rains delay could instead facilitate the disease incidence.

Adaptation scenarios

In our study, different adaptation strategies have emerged, characterised by different level of reforestation or avoided deforestation in the Taita Hills and Jimma, respectively. Despite constrained between increasingly arid lowlands and limited middle-high lands, the Taita Hills are located in a favourable location, at the cross of renewed international trade routes, which could provide an advantage for the transition towards either a market-based agricultural system or a conservation-recreational business oriented system. To comply with climate change adaptation and sustainable development goals, traditional livelihood systems should be modernised through improved capacity and climate smart agronomic practices (e.g. agroforestry), which could ensure provision services, in particular food and water, without further depleting regulation services and biodiversity (FAO 2015). However, under the food production scenario the sustainability and system resilience could be at risk over long term. For example, farmers could be encouraged to grow crops in marginal areas by new technologies availability. Moreover, if farming suitability decreases in the low zone, the mountain regions could attract migrants who are not familiar with the climate smart farming approach. Investment in innovation, education, tourism and services, along with incentive schemes such as watershed service payments and REDD+ (Korchinsky et al. 2011) could support efforts for increasing forest cover and enhanced landscape ecosystem service provision, as envisaged in the green integration scenario. This requires a deep transformation of the community behaviours and cultural values, and the development of policies integrated across the elevation gradient, so that income generating activities are increasingly focused on the low zone or elsewhere, resulting in partial re-naturalisation of the landscape. High population density and pressure may undermine the feasibility of adaptive transformation in the Taita Hills. A mixed-scenarios adaptation strategy coupling subsistence to market-based farming transition

with gradual re-greening, e.g. through agroforestry expansion, could be more appropriate for ensuring long term resilience.

Compared to the Taita Hills, the Jimma rural areas are more remote and isolated, far from markets (particularly from coffee auction sites) and tourism routes; pursuing climate change adaptation and system resilience will require greater efforts on the social and ecological system development. On the other hand, lower population density than in the Taita Hills provides higher chances for adaptive transformation and system resilience enhancement. Despite the positive effect of coffee presence in limiting the conversion of forest to annual-crop agriculture, intensification of coffee management under the coffee industry scenario could threaten forest dependent species biodiversity (Norfolk et al 2017b), including the genetic diversity of wild coffee (Hylander et al. 2013). Moreover, in the coffee industry scenario farmers feared the increased dependence on food purchasing and on external market price fluctuations. On the contrary, in the agroforestry scenario shading and maintaining forested land cover around coffee plots can mitigate the impacts of temperature increase (Garedew et al. 2017b) with positive cascade effects on decreasing coffee berry disease incidence (Bedimo et al. 2008) and other ecosystem services (Cerdeira et al. 2016,). Selection of shading tree can contribute to climate regulation through carbon sequestration, and potentially generate payments from carbon markets (Denu et al. 2016). Expansion of agroforestry system is also expected to provide better food nutritional value, allowing cultivation of fruits and beans along with cereals, and maintain diversification of cash-crops.

The presented adaptation scenarios may apply more generally to African mountain socio-ecological systems facing climate change along with sustainable development challenges (Leal Filho et al. 2017). Agroforestry has potential for overcoming trade-offs

across ecosystem services and biodiversity, and support communities adaptation capacity and resilience. Several barriers have stopped its expansion across Africa, including the productive and environmental performance, socio-cultural and political prerequisites, and opportunity cost (Mbow et al. 2014). Our findings suggest that in absence of a readiness processes for anticipating potential climate crises and barriers to adaptation, such as those supported by place-based scenario analysis, smallholder farmers may even abandon the existing agroforestry systems, to open up more land for staple crops and ensuring food security. Alternatively, in montane areas suitable for high value cash-crops, climate changes impacts may accelerate the replacement of traditional farming systems by commercial farming. While food access could be enhanced by wages security, food security is actually a result of complex synergies of economic, social, and cultural factors (Dam Lam et al. 2017).

Conclusions

Future trajectories of socio-ecological systems in tropical mountain ecosystem will largely depend on societal willingness and capacity, at different levels, to undertake the changes needed to reduce the impacts of climate and land management change. Through a participatory scenario development process we engaged mountain communities in the Taita Hills, Kenya and Jimma, Ethiopia in envisioning potential impacts of global climate change and local land changes, and identifying and negotiating trade-offs between desirable and undesirable goals. We found that business as usual coping strategies could lead to disruption of local livelihoods system in the two study areas. Different alternative adaptation pathways emerged that would generally require either transformation of traditional farming, e.g a move to modern food production or agroforestry expansion, or a radical shift to new livelihood systems, e.g. a migration of human activities from higher to lower elevation or shift to coffee plantations. These

alternatives may present trade-offs for ecosystem services, in particular between provisioning, regulating services, and biodiversity. The identified adaptation alternatives could possibly inform climate change adaptation and mitigation strategies. Our studies highlighted the importance of developing transdisciplinary approaches in sustainability science and in building local capability to anticipate an uncertain future, and of promoting synergies between climate, development and conservation actions at local scale.

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Table 1. Climate parameters baseline and projected values for the Representative Concentration Pathway (RCP) 4.5 scenario by mid-21st century (IPCC 2014), derived from 1-km resolution temperature and rainfall spatial grids (AFRICLIM 3.0, Platts et al. 2015). The mean and range (in parenthesis) of the variables spatial mean across each study area are reported.

	Taita Hills		Jimma	
	Baseline	RCP 4.5 to Baseline change	Baseline	RCP 4.5 to Baseline change
Mean annual temperature (mean of monthly means, °C)	22.0 (16.7 - 24.9)	1.8 (1.8 - 1.9)	18.7 (17.1 - 20.8)	2.3 (2.2 - 2.4)
Mean annual rainfall (sum of monthly rainfall, mm)	1022 (644 – 1442)	71.9 (44 – 94)	1782 (1642 – 1839)	-31 (-57 - -11)
Rainfall seasonality (standard deviation over monthly values, mm)	60 (40 - 91)	8 (5 - 10)	106 (98-114)	3 (+1 – 5)
Number of dry months (Dry/arid if monthly moisture index <0.5)	7 (4 – 8)	-0.1 (-1 – 1)	4 (4 – 5)	0.4 (0 – +1)

Table 2 – Surface of land use and land cover classes (hectares) in the Taita Hills in the 2011 baseline map (Heikinheimo 2015) and in the business as usual (BAU), food production (FP) and green integration (GI) scenarios maps¹. Changes for water were not modelled, though we could expect a change in water production at catchment level and relative changes in water surface.

Land use and land cover class	Baseline	BAU	FP	GI
Cropland	38873	40834	45193	40609
Shrubland	16332	16028	14778	15427
Thicket	19813	18668	14893	18383
Woodland & Agroforestry	6076	5296	5976	6044
Plantation Forest	2495	2938	2529	2392
Indigenous Forest	803	633	1020	1527
Grassland	2210	2209	2211	2211
Bare soil & Built up Areas	854	850	856	863

¹ Expected future land use and land cover changes by mid21st-century were quantified over a 35-year period from the baseline.

Table 3 – Surface of land use and land cover classes (hectares) in the Jimma area in the 2008 baseline map (Hailu et al. 2014, 2015b) and in the business as usual (BAU), industrial heavy managed coffee plantations (CI) and semi-managed coffee and agroforestry (AGF) scenarios¹.

Land use and land cover class	Baseline	BAU	CI	AGF
Indigenous Forest	29768	17900	27881	27904
Cropland	9490	18273	9563	8686
Closed to Open Wood Vegetation	631	320	0	0
Grassland	2000	1410	1406	1406
Exotic Forest	480	784	480	480
Built-up areas	155	348	155	155
Degraded land ^a		3286	0	0
Coffee plantation ^a		203	1701	200
Agroforestry ^a		0	1338	3693

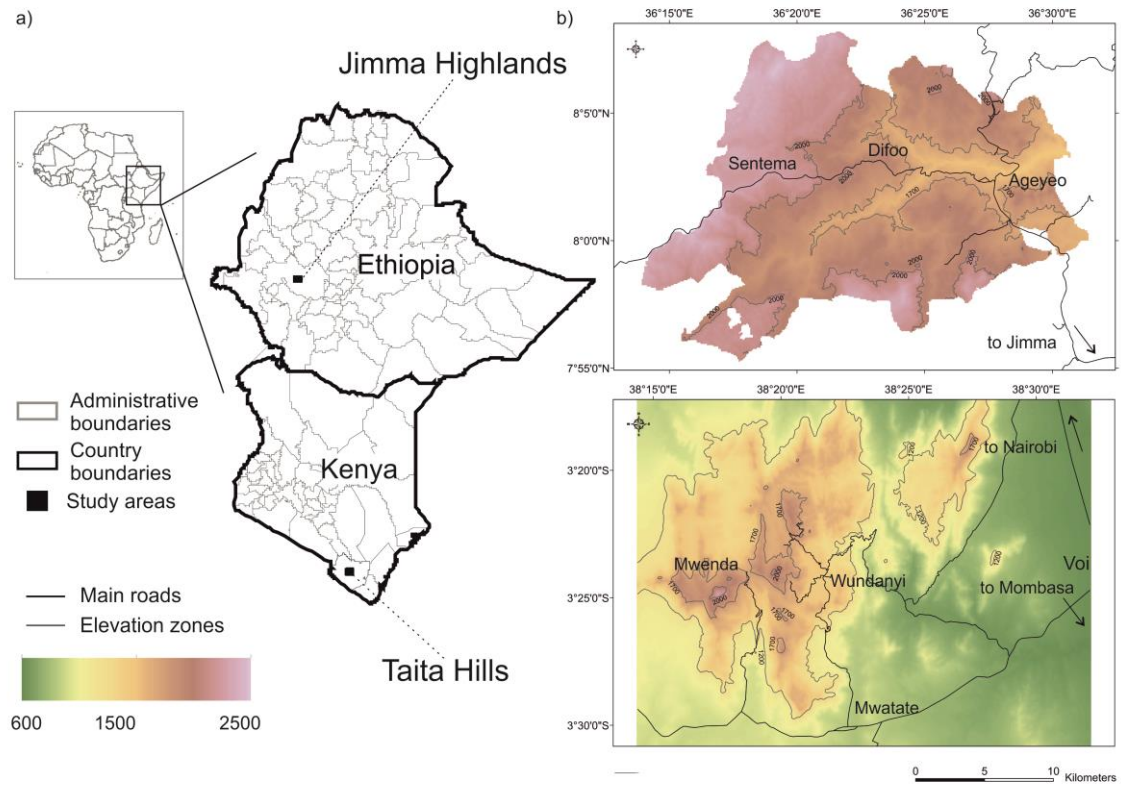
^a Classes not represented in the baseline map and added by workshop participants during scenarios development

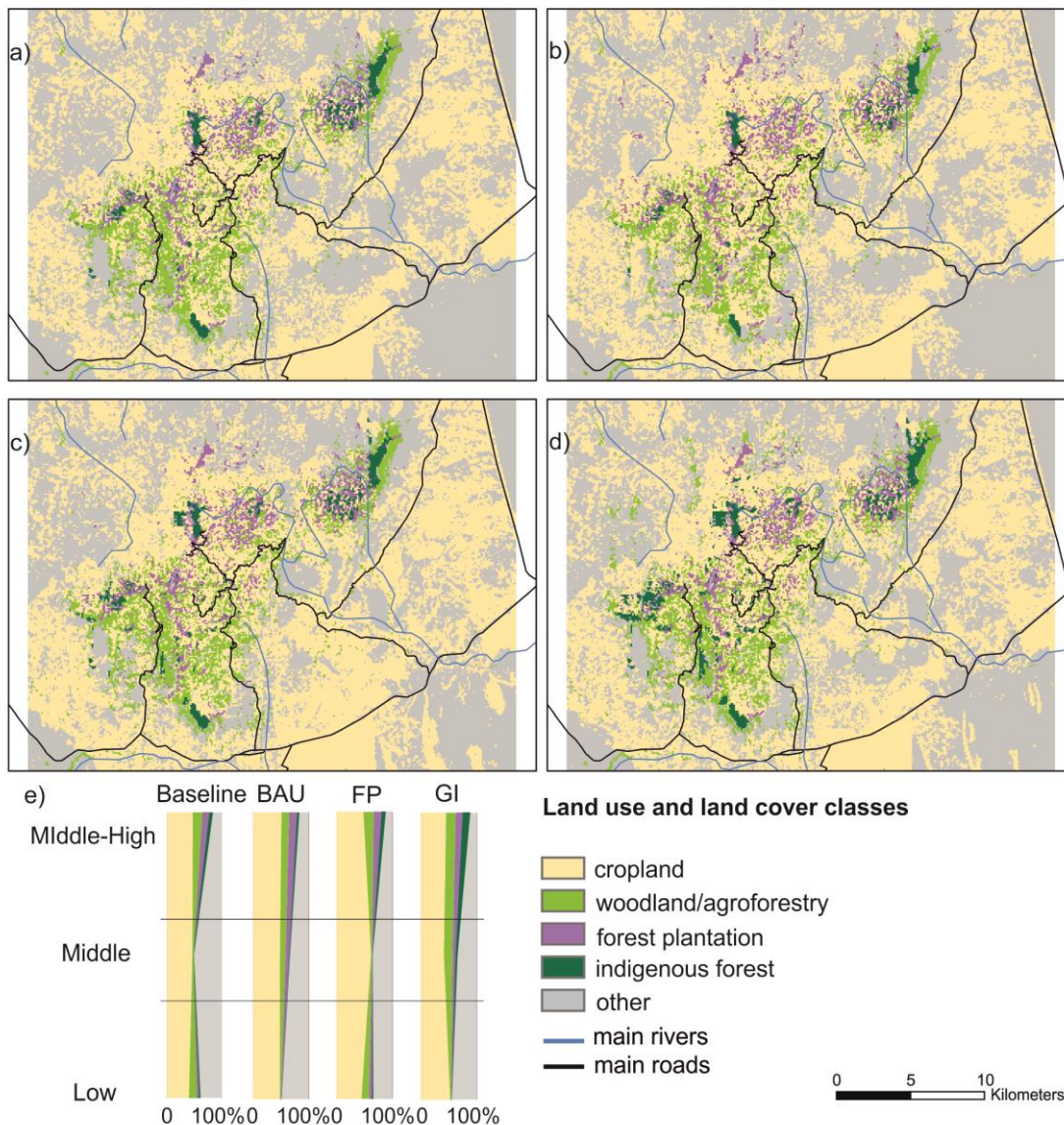
¹ As Table 2.

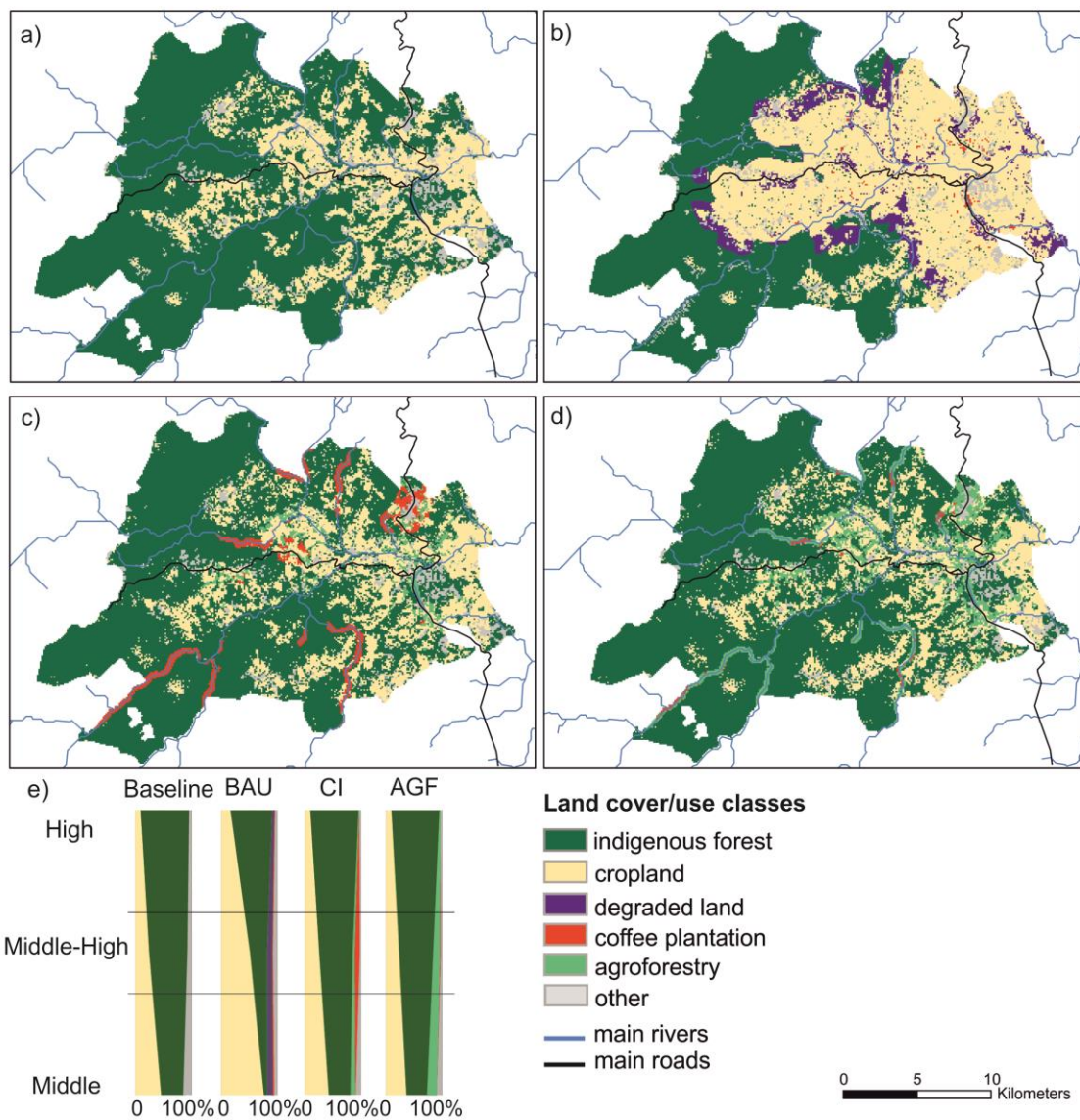
Figure 1. Location of study areas in East Africa (a), and elevation (SRTM-90, Javier et al. 2008) and contours of the reference elevation zones in the Taita Hills and Jimma study areas (b).

Figure 2. Land use and land cover in the Taita Hills study area in the baseline (a, modified from Heikinheimo 2015), and in the business as usual (BAU, b), food production (FP, c) and green integration (GI, d) scenarios. At the bottom (e), share of land use and land cover classes (%) in the low (<1200 m a.s.l.), middle (1200-1700 m a.s.l.) and middle-high (>1700 m a.s.l.) zones.

Figure 3. Land use and land cover in the Jimma study area in the baseline (Hailu et al. 2014, 2015) and in the business as usual (BAU, b), industrial coffee plantation (CI, c) and agroforestry with semi-managed coffee production (AGF, d) scenarios. At the bottom (e), share of land use and land cover classes (%) in the middle (<1200 m a.s.l.), middle-high (1200-1700 m a.s.l.) and high (>1700 m a.s.l.) zones.







Supplementary 1: Scenarios storylines and qualitative assessment of potential impacts on biodiversity and ecosystem services

Supplementary 1a. Scenarios in the Taita Hills

SCENARIO 1 – **Business as usual (BAU)**: There is no common and proper strategy for the long term adaptation implemented, such as decrease of vulnerability and enhancement of resilience, rather individual coping strategies and not-integrated community interventions persist. Cropland expands at lower rate than for the 2003-2011 period, forest and woodland is cleared at higher rate.

Participants' perspectives (Table S1.1): Potential positive effects of increased temperature and rainfall are disrupted by increased frequency of unpredictable and extreme events and uncertainty of seasonal patterns, and by potential acceleration of diseases spread. Effects of climate variability are strongly affecting livelihood in every sector, including farming, livestock, and tourism. Low capacity of managing and retaining water plays a central role in reducing productivity and undermining infrastructures. In this scenario biodiversity is threatened by increased pressure on forests and woodlands, human-wildlife and human-human conflicts are exacerbated. Population growth rate was debated. It was expected to either decrease, following abandonment, or increase at low rate because of increasing immigration: in harsh climate conditions the Hills could still represent a refuge for many people from the lowland. This latter interpretation seems to prevail.

SCENARIOS 2 and 3 - **Adaptation**: An integrated landscape centred strategy is implemented and interventions are realised to increase resilience and adaptation capacity to climate change, such as improving water use and retention, land management, productivity, post-harvest yield and value chains.

Participants' perspectives (Table S1.2): Climate effects are compensated through an integrated approach encompassing governance, land and water management, value chains and alternative livelihood development. This includes the rehabilitation of already existing infrastructure for water retention along with tree planting. New varieties are grown to improve water use, and more resistant to drought and to shorter seasons. Population is expected to increase, more transformation of the landscape are expected (e.g. new farmland and urban), but the impact on biodiversity would be positive, following better forest protection and restoration.

Two adaptation scenarios were simulated, to represent the two main expectations expressed in the scenario development stage, forest and agriculture system improvements. Proposing more than one adaptation scenario was also meant to encourage Participants' discussion on feasibility and potential trade-offs between the two pathways.

Food production (FP): this adaptation scenario focuses on agriculture, following the idea that improved water and land management could actually boost agriculture expansion in the hills, including cropland and agroforestry, along with a little increase of forest cover. Cropland expands at similar rate as for the 2003-2011 period, moderate reforestation is applied.

Green integration (GI): this scenario focuses on forest and ecosystem services, and it envisages that the hills are designated to protect and enhance the water catchment and human activity are either converted (e.g. to eco-tourism) or displaced (e.g. in the lowland or on the coast). Cropland expands at lower rate than for the 2003-2011 period, high reforestation is applied.

Table S1.1. Drivers of socio-economic and environmental trajectories in the business as usual (BAU) and in the adaptation scenarios according to workshop participants in the Taita Hills. Potential impacts ranking from Low to High reflects the expected drivers occurrence and magnitude of driven change.

Drivers in the BAU scenario	Drivers in the adaptation scenarios	Potential impact
Inadequate technology; inadequate utilization of agricultural resources, inadequate extension services Unsustainable tree harvesting method; encroachment of forests, forest fires, illegal logging, lack of suitable alternative to forest products Poor water management Fertility loss Agricultural land demand Population growth	Technology improvement and innovative practices Irrigation Optimal use of available resources related to agriculture Sustainable forest production Application of forest economics principle Professional trainings Proper conservation measures	High
Overuse of pesticide Low ownership rights	Large scale agriculture Increased livestock and crop production	Mid

Climate	Industrialization	
Low industrial production	Increased value addition on all value chain	
Farming in not suitable land	Soil conservation	
	Increased vegetation cover	
Subsistence livestock husbandry system, not specialised	Farm plans in place	Low
Urbanization; Mining activities	Community awareness	

Supplementary 1b. Scenarios in the Jimma Highlands

SCENARIO 1 - Business as usual (BAU): Climate changes are generating unusual conditions in the area which affect coffee production. Strategy for long term adaptation is failing in face of existing development gap, governance challenges and cultural barrier in taking up innovation. Individuals react to the crisis through coping strategies targeting food security. Deforestation and cropland expansion occur at similar rate as the 2003-2008 period (1% annual rate), but at the same time existing cropland is degraded.

Participants' perspectives (Table S1.2): In this scenario, decline in water sources, in crop and livestock productivities are expected along with the increase of some pest diseases and the reduction of others. As consequence, poverty, health problems and social disturbance (e.g. human-human conflicts) escalate. Most affected sectors are agriculture, wildlife and forestry, education, and health. Despite these potential challenges, population is expected to grow and consequently more forest is converted into farmland at high rate, and production shifts from cash crops (expected to be less productive) to staple food. Income and biodiversity decline.

SCENARIOS 2 and 3 - **Adaptation**: An integrated landscape centred strategy is implemented and interventions are realised to increase resilience and reduce vulnerability to climate change.

Participants' perspectives (Table S1.2): In this scenario, resilience to climate change as well as other stressors is enhanced through a general improvement of the production system (from seed variety to market accessibility and infrastructure), and of social services and infrastructure (e.g. roads, capacity building centres). Effects on population growth were debated, but expectations of population increase finally prevailed. The women group were less optimistic than the other groups of men (farmers or academics

and officials) and expected in this scenario the same level of land use change and biodiversity as in the current situation.

Two adaptation scenarios were simulated, to represent two main trajectories expressed in the development stage: expansion of industrialised and heavily managed coffee production, or expansion of agroforestry system.

Coffee industry (CI): In this scenario, given the high risks in coffee production induced by changing climate conditions, industrial companies step in as they can afford the price of breed improvement, seed protection, high rate of plant turn over, processing and post-harvest management, and take over the entire production. Local farmers shift to become workers in the private companies or out-growers. Though this support households cash flow and local services improvement, local communities are highly dependent on external actors. Deforestation occur at lower rate (ca. 0.25% annual rate) than in the 2008-2003 period, and is mainly pushed by commercial coffee farming establishment.

Agroforestry (AGF): In this scenario, increased aridity and rising temperature are tackled through a shift to agroforestry. Rather than forest and cropland being neatly separated by thin transition margins, agroforestry system expands over both forest and open cropland. This ensures the mitigation of climate effects in suitable areas for coffee production, which continues through a semi-managed system. Deforestation occur at lower rate than in the 2008-2003 period (ca. 0.1% annual rate).

Table S1.2. Drivers of socio-economic and environmental trajectories in the business as usual (BAU) and adaptation scenarios according to workshop participants in the Jimma area. Potential impacts ranking as in Table S1.1.

Drivers in the BAU scenario	Drivers in the adaptation scenarios	Impact
Increased diseases pressure; old age of coffee resulting in low/no yield	Improved farming system	High
Continued deforestation and degradation following increased demand of forest and no tree replanting	Improved productivity	
Lack of grazing land	Improved coffee variety (e.g. disease resistant variety)	
Social conflicts	Use of inputs	
Inadequate production technology, lack of storage and conserving system;	Proper storage system	
Productivity decline	Improved animal husbandry and breeds	
lack of improved livestock breeds	Improved resources management	
	Increased community awareness, knowledge, participation	Mid
	Construction of institutions Decreasing population	
Instable crop price, expected economic benefit decline;	Use certified seeds	

Decreased area sustainability

Poor farming system, use of local seeds

High nutrition value food production

Honey production

Proper post-harvest handling

Improved coffee management practices

Increased forest cover

Culture

Saving of credit

Improved infrastructures

Inadequate access to socio-economic services; lack of

budget for infrastructures; remoteness

population growth

Conservation

Low

Supplementary 1.c. Participatory qualitative assessment of scenarios potential impacts on biodiversity and ecosystem services

In the final workshops, after scenario outputs presentation, participants' groups were required to evaluate ecosystem services (ES) and biodiversity impacts by using qualitative judgement (ES are "equal", "improved", "very much improved", "declined", "very much declined" compared to the baseline). Since participants mainly used the 3 scale categories "equal", "improved", "declined", in assessing results we only referred to these categories, which were attributed scores of 0, 1, and -1 respectively for the purpose of comparing results amongst participant groups.

We calculated impacts scores for provisioning, regulating and cultural services by averaging the ES scores within each category. The biodiversity score was based on a single evaluation and therefore can only assume 0,1, -1 scores. Scores attributed by different groups were then compared and discussed (Fig. S1 a-d).

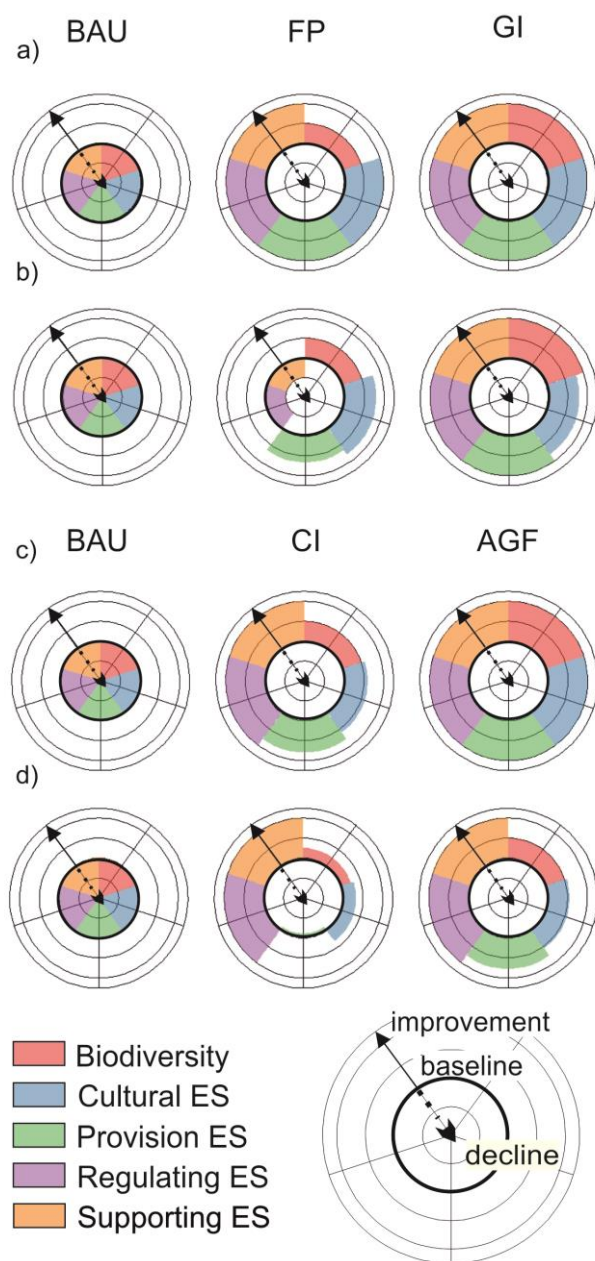


Figure S1. Qualitative assessment of changes in ecosystem services and biodiversity states expressed by different stakeholder groups under alternative scenarios in the Taita Hills (a and b, farmers and local authorities mixed groups; BAU = business as usual, FP = food production and GI = green integration scenarios, respectively) and in Jimma (c, academics and officers, d, men and women farmers; BAU = business as usual, CI = coffee industry, AGF = agroforestry scenarios, respectively). State changes were expressed as improved or depleted or equal compared to the baseline.