IR3S *Integrated Research System for Sustainability Science*

SPECIAL FEATURE: ORIGINAL ARTICLE

Future Scenarios for Socio-Ecological Production Landscape and Seascape

CrossMark

Future land use management effects on ecosystem services under different scenarios in the Wabe River catchment of Gurage Mountain chain landscape, Ethiopia

Mesfin Sahle[1,5] (iD) · Osamu Saito[2] · Christine Fürst[3] · Sebsebe Demissew[4] · Kumelachew Yeshitela[1]

Abstract

In this study, we have modeled and examined future land use management effects on ecosystem services in the Wabe River catchment of the Gurage Mountain chain landscape, Ethiopia. In addition to the climate-resilient scenario designed to meet the strategic plan of Ethiopia, the business as usual (BAU) and an alternative agroforestry scenario were modeled for the year 2030 to align with the government long-term development plan. Through the statistical and biophysical modeling approach, this study quantified and mapped the food production, water provision, carbon storage, and sequestration and sediment retention ecosystem services. The land use land cover and the other datasets were obtained from various primary and secondary sources, and prepared according to the models requirement. The future scenarios were modeled through the Land Change Modeler for ArcGIS and InVEST Scenario Generator models. The simulated BAU scenario result revealed that all of the ecosystem services decreased from the baseline status. In contrast, implementation of the climate-resilient strategy could enhance the existing status of ecosystem services. In the agroforestry scenario, all of the quantified ecosystem services increased even more than the climate-resilient scenario. We conclude that landscape management activities described in the climate-resilient strategy could ensure sustainable production while conserving the environment. However, we recommend the enset-based agroforestry system expansion, which could boost food production and enhance other ecological services in the catchment. Further studies are suggested on the expansion of this system in the catchment and similar parts of Ethiopia.

Keywords Enset-based agroforestry · Business as usual · InVEST · Synergies · Land use models · Landscape planning

Introduction

The change in land use land cover (LULC) is one of the essential issues in global environmental change and sustainable development (Yirsaw et al. 2017). The interaction of LULC with climate, biogeochemical cycles, biodiversity, ecosystem processes, and human activities resulted change in LULC [IGBP (The International Geosphere-Biosphere Programme) 1999], which may occur on various spatial and temporal scales (Reid et al. 2000). The changes in LULC can significantly influence economic growth, water quality and availability, the spread of invasive species, habitats and biodiversity, carbon fluctuations, and climate variability (Slonecker et al. 2013). However,

✉ Mesfin Sahle
   mesitago@gmail.com

1 Ethiopian Institute of Architecture, Building Construction and City Development (EiABC), Addis Ababa University, P. O. Box: 518, Addis Ababa, Ethiopia

2 United Nations University Institute for the Advanced Study of Sustainability, Tokyo, Japan

3 Institute of Geosciences and Geography, Martin Luther University Halle-Wittenberg, Halle, Germany

4 Department of Plant Biology and Biodiversity Management, College of Natural Sciences, Addis Ababa University, Addis Ababa, Ethiopia

5 Department of Natural Resource Management, Wolkite University, Wolkite, Ethiopia

⬚ Springer

the changes in LULC especially at the regional and local level can be managed through policies and environmental planning decisions. Land use management helps to optimize production in the sense of a sustainable maximization of outputs, and holds a conservation objective for maintaining the available properties, potentials, and outputs (Verheye 2009). Thus, monitoring and mediating the negative consequences of LULC change while sustaining the production of essential resources has become a major priority of researchers and policymakers around the world (Ellis and Pontius 2007).

The UN Division for Sustainable Development encourages countries to develop green economic growth strategy [UN-DESA (United Nations Department of Economic and Social Affairs) 2012], and several countries started to develop green economic development strategy for sustainable development of their nations. Ethiopia is one of the countries which developed a green economic strategy, the so-called climate-resilient green economy (CRGE), to build a green economy by 2030 (CRGE 2011). The CRGE strategy document stated that following the conventional development path would, among other adverse effects, result in a sharp increase in greenhouse gas (GHG) emissions and unsustainable use of natural resources. The green economy plan is based on four pillars such as improving crop and livestock production practices for higher food security and farmer income while reducing emissions; protecting and re-establishing forests for their economic and ecosystem services; expanding electricity generation from renewable sources of energy for domestic and regional markets; and leapfrogging to modern and energy-efficient technologies in transport, industrial sectors, and buildings (CRGE 2011). The development of Ethiopia largely depends on the agricultural sector, and contributes for 72.7% of employment and 35.8% of GDP [Central Intelligence Agency (CIA) 2018]. According to Brown et al. (2012), the agricultural and forestry sectors are the main sources of GHG emissions in Ethiopia, and thus, most of the CRGE strategies are focused on the land use managements of agricultural land.

Land conversion and land use intensification are the major drivers of ecosystem service depletion or enhancement (Foley et al. 2005; Pereira et al. 2012; Fürst et al. 2013). More sustainable land management strategy could ensure the continued provision of ecosystem services. Thus, understanding the effects of land management on provision of ecosystem services is crucial in projecting the consequences of policies and decisions, and could help to find alternative planning solutions. To evaluate the sustainability of land management strategies, in-depth information about the various impacts on ecosystem services is needed.

Scenarios and models can provide an effective means of addressing relationships between nature, nature's benefits to people, and good quality of life, and can thereby add considerable value to the use of the best available scientific, indigenous, and local knowledge in assessments and decision support (IPBES 2016; Díaz et al. 2018). By spatially modeling the future scenarios, we can better understand the impact and uncertainties of various land use plannings and policies in a wide range of potential futures before they occur (IPBES 2016; Gibson and Quinn 2017; Kindu et al. 2017). In recent times, the requirement of future information on the status of ecosystem services motivates many institutions and scientists to InVEST their resources on the development of models for ecosystem services quantification and mapping—and for future prediction and development of alternative scenarios as well. This helps several researchers to engage in scenario analysis to address the effects of future land use change on ecosystem services and human well-being for decision making (Petz and van Oudenhoven 2012; Estoque and Murayama 2012; Geneletti 2013; Shoyama and Yamagata 2014; Han et al. 2015; Yirsaw et al. 2017; Kindu et al. 2017). Most of the above studies are focused on the prediction of land use change based on past trends and planning alternative scenarios for evaluating their effects on ecosystem services. However, studies to evaluate the long-term development strategy of countries on the sustainable provision of ecosystem services for informed decision making to the government are rare.

The present study was thus written to evaluate the CRGE of Ethiopia on the provisions of ecosystem services by considering the Wabe River catchment of Gurage Mountain chain in Ethiopia. For comparison, the study also simulates the future LULC patterns based on the past trend as a business-as-usual (BAU) scenario, and modeled another alternative agroforestry scenario. The findings from this study are intended to better illuminate the future effects of LULC dynamics, strategic planning, and other alternative scenarios on ecological services and human well-being in the catchment area, and to choose an alternative land use management mechanism before ending the strategic period.

Materials and methods

The study area

The Gurage Mountain chain in the south central part of Ethiopia extends from the South West Shewa in Oromia Region (in the North), the Gurage and Silte zones (centrally located) to the Hadiya zone in the Southern Nations, Nationalities, and Peoples Region (in the South). The mountainous highland divides the Gurage zone into east and west. The mountain chain forms a watershed boundary
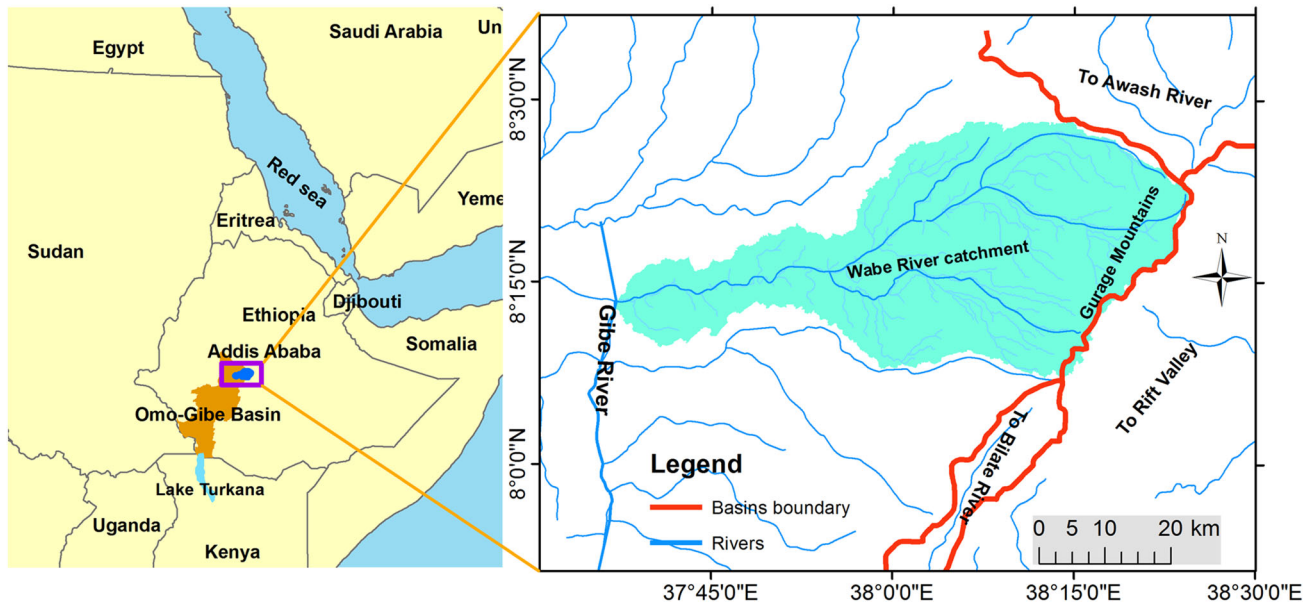
Fig. 1 The location map of Wabe River catchment in Ethiopia

between the Omo–Gibe River basin in the West, the Great East African Rift Valley in the East, the Awash River basin in the North, and the Bilate River basin in the South. The Wabe River catchment is a sub-basin of the Omo–Gibe in the western parts of the Gurage Mountain chain (Fig. 1). The catchment is located between 08°21′ and 08°30′N and 38°05′ and 37°49′E. The Gurage Mountains, with altitudes of 3611 m above sea level, account for the highest area in the catchment, and the lowest altitude of 1014 m is found in the Gibe River. The catchment covers a drainage area of 1860 km². The maximum temperature of the Wabe River catchment ranges from 20 °C (in the wet season) to 39 °C (in the dry season), and the minimum temperature ranges from 0 °C to 19 °C, with an average temperature of 18 °C. The mean annual rainfall ranges from 966 to 1534 mm [National Metrological Services Agency (NMA) 2016].

Land use within the Wabe River catchment is primarily oriented to enset-based subsistence agriculture. In the catchment, the intensification of agriculture has a serious impact on the conservation and sustainable utilization natural resources such as forest (Woldetsadik 2003). Almost every plot of land is used for agricultural practices. The steep slope including mountains peaks are used for cereal farming which have a negative impact in comparison to the root crops. According to Sahle et al. (2018a), the catchment carbon sequestration is less than the current GHG emission level. Thus, evaluation of the Ethiopian government CRGE and other land use management effects on ecosystem services in such complex type of land use with a high LULC dynamics are very important for understanding of planners and decision makers in the catchment and in the other parts of Ethiopia.

LULC changes

The LULCs and their changes in the Wabe River catchment were obtained from the supervised classification of Landsat images from 1986 (TM) and 2017 (OLI) with the spatial resolution of 30 m using ERDAS Imagine software. Before classification, pre-image processing operations such as image restoration, geo-referencing, and image enhancement were done. The accuracy was assessed through accuracy assessment tools in the ERDAS Imagine software using the representative points after classification. The assessment is based on statistical approach which examines the agreement between the reference points with the classified map. The reference points were collected from the field using Garmin 60 model GPS and visual interpretation of the raw images with the help of personal knowledge of the study area and high resolution imageries such as Google Earth, SPOT, and Sentinel 2. The classification was done with an overall accuracy of 91.6 and 88.4% for the years 1986 and 2017 images, respectively. The identified major ten LULCs are grazing land, enset-based agroforestry, crop land, wetland, bare land, built-up area, Afro-alpine and Subafroalpine vegetation, forest, shrubland, and woodland (Table 1). From these, grazing land and cereal crop cover large area (Fig. 2).

Future scenario analysis

This study considered the CRGE strategy of Ethiopia as a climate-resilient scenario, and converted the strategy into a spatially explicit manner using the LULC of the Wabe River catchment to show its effect on carbon storage and

Table 1 Description of the identified LULCs in the Wabe River Catchment

LULC	Description
Bare lands	Areas of land that are poorly covered by vegetation due to erosion, overgrazing, and cultivation
Grazing lands	All areas covered mainly with natural grass and small herbs/shrubs.
Cereal crops	Areas of land prepared for growing cereal crops. This category includes areas currently under crop cultivation, and land under preparation.
Forests	Areas covered by natural and man-made trees with minimum size of 0.5 ha.
Woodlands	Scattered trees mainly dominated by *Acacia* spp found in the lower altitude.
Built-up area	Residential, commercial, industrial, transportation and facilities
Shrubland	Area covered by small trees, bushes, and shrubs mixed with grasses; less dense than forests
Wetland	Areas that are waterlogged and swampy in the wet season, and relatively dry in the dry season
Enset-based agroforestry	Areas dominated by enset crop growing in the home garden with other agroforestry crops such as fruits, vegetables, chat, coffee, etc.
Afro-alpine and Subafroalpine vegetation	Area covered by shrubs mixed with grasses such as *Erica arborea* in the higher altitude
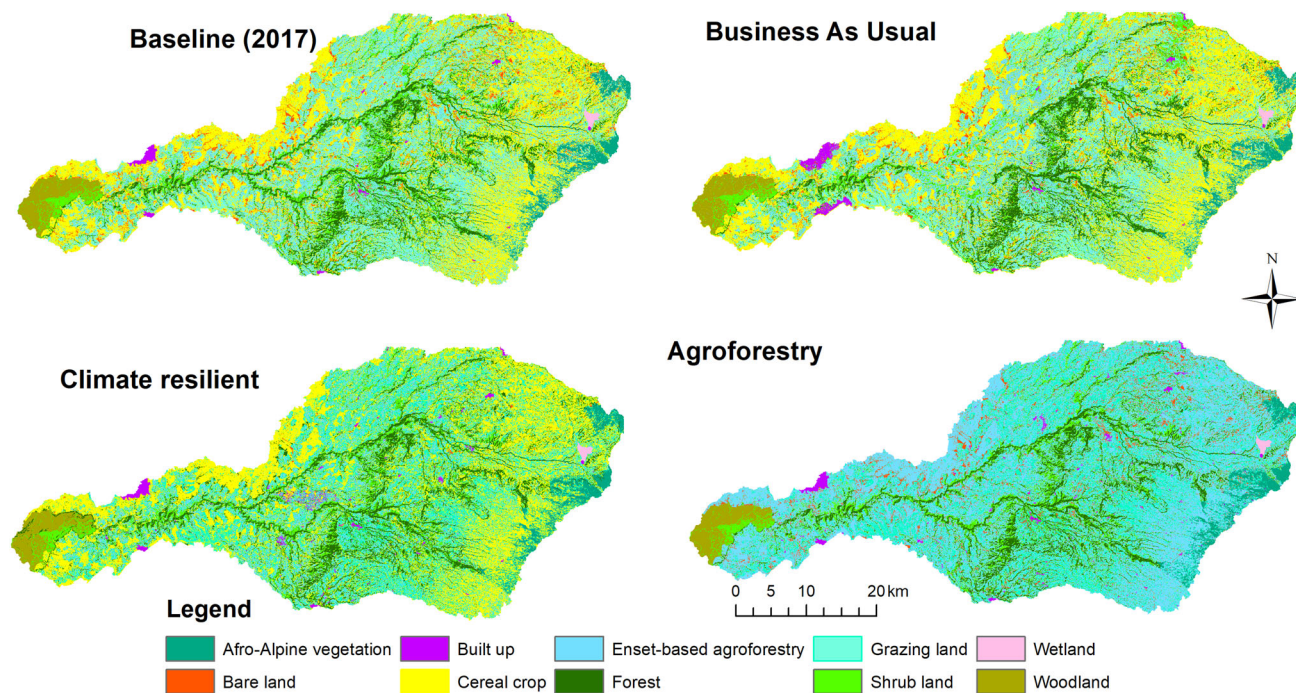
Fig. 2 The LULC map of the Wabe River catchment in the baseline and at different scenarios

sequestration and other ecosystem services. For comparison, additional scenarios such as BAU and agroforestry were developed. The scenarios were modeled for the period of 2030 to match with the country's (Ethiopia) long-term green economy development strategy.

Business-as-usual scenario

To explore the changes in the future, the BAU scenario was developed through the Land Change Modeler of ArcGIS (LCM). LCM is an innovative land planning and decision support software, which allows rapid analysis of land cover change and simulates future land change scenarios (Eastman 2006; Odindi et al. 2012). It is based on the Markov Chain Analysis to characterize the land change processes and predict LULC change under a BAU scenario. The algorithms in the LCM integrate the functions of the cellular automata (CA) filter and Markov process, using conversion tables and conditional probabilities from the conversion map applied to simulate and forecast the states of LULC change. The BAU scenario was developed from spatially explicit simulation of land use change based on

the empirical analysis of location suitability combined with the dynamic simulation of completion between the spatial and temporal dynamics of land use. Location probability of each land use type was addressed based on the logistic regression analysis. Driving factors of elevation, slope, distance to river, distance to roads, distance to towns, and population density were considered to evaluate the sub model. Elevation and slope were derived from the digital elevation model obtained from the Shuttle Radar Topography Mission satellite image. River, roads, and population data were obtained from the Central Statistical Agency (CSA) of Ethiopia. The existing towns were extracted from Landsat imagery.

The BAU scenario was designed mainly based on assumptions of a continuation of LULC conversion rates over the past 30 years in the studied landscape. The transition suitability map, which was used to predict the LULC in 2017 and to simulate the distribution in 2030, was generated based on the main transitions that occurred among the LULC categories from 1986 to 2017. To determine CA filters, the neighborhood definition of the regular 5×5 contiguity filter was used. Kappa statistics were used to assess the accuracy of the forecasted 2030 LULC map to evaluate its agreement with the actual 2017 LULC map. During assessment, the 2017 LULC map acted as the reference map (reality), while the simulated map (2030) was the comparison map.

Climate-resilient scenario

For the development of this scenario, the study used the Natural Capital Project's InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) Scenario Generator model. This model provides a relatively simple method of generating scenarios based on land suitability. The major components of the input are: (1) the transition likelihood, (2) the physical and environmental factors that influence change, and (3) the quantity of anticipated change under a given scenario (Sharp et al. 2016). The quantity of change was determined by the demand for land estimated from the strategy document (CRGE 2011). Each scenario transition matrices was built to explain the relative likelihood of one land cover changing into another in 2030. Using spatial proximity from the 2017 LULC map and the likelihood of change as defined by the matrices, the InVEST Scenario Generator modeled how the LULC could change under the climate-resilient land use management scenario. The model converted each of the LULC pixels based on their suitability values using each transition matrix. Starting from the cover type with the highest priority, the total percentage of LULC change was read from the matrix, and pixels were converted starting from the highest priority and likelihood of change. After each cover is processed, the converted

pixels are masked so that they are not available for conversion again.

In the CRGE strategy, it has been planned to limit the soil-based emissions from agriculture and decrease the pressure on forests from the expansion of land under cultivation. Intensification of agriculture through the usage of improved inputs, better residue management, and the creation of new agricultural land in degraded areas through irrigation are the strategies to decrease requirements for additional agricultural land that would primarily be taken from forests. Increasing animal value chain efficiency, supporting consumption of lower-emitting sources of protein, mechanizing draft power, and managing rangeland are the strategies to increase the productivity and resource efficiency of the livestock sector. For sustainable development of the forestry sector, reducing demand for fuel wood, increasing afforestation, reforestation and forest management, and promoting area closure are the strategies to reduce carbon emissions. Since most of the strategies are management practices on the existing LULCs when developing the scenario, large areas of the LULCs remain unchanged. But, half of the existing bare land near the river was considered to be converted to cereal crop. The Wabe River catchment has large areas with slope $> 30°$ with undulating terrain and bare land, which are mostly degraded. Thus, in this scenario, the degraded bare land and high slope areas were considered for rehabilitation. The forest development in these areas increased the forest cover by 20%. Since the management activities could reduce the GHG emissions, a 10% increase in the carbon stock was assumed while quantifying the service.

Agroforestry scenario

In 2017, the area used for enset-based agroforestry in Wabe River catchment is 17.6%. Reports show that hectarage production of food in enset-based agroforestry is higher than the cereal crop production in the Gurage zone (CSA 2017). In addition to food production, this type of land use has high ecological value in the zone, and in the other agroforestry practice areas of Ethiopia such as local climate regulation, erosion control, and scenic beauty. Thus, to obtain multiple functions of enset-based agroforestry, expansion of this type of land use could enhance the benefits of communities. The study assumed that since the communities are not new for enset-based agroforestry, they can possibly replace their cereal crop with this type of land use through policy interventions. Based on this assumption, this study modeled an alternative scenario by converting all of the existing cereal crop areas into enset-based agroforestry. To model the scenario, the InVEST Scenario Generator model was used.

Quantification and mapping of ecosystem services

Using the maps of future land use patterns based on the LCM and InVEST Scenario Generator, indicators were calculated to assess the change in ecosystem service provisioning with land use managements. Four indicators were selected based on the characteristics of the study area: (1) food production; (2) carbon storage and sequestration; (3) erosion control; and (4) water provision. These ecosystem services represent the main categories of regulating (carbon sequestration and erosion control) and provisioning (food production and water provision) services. The selected indicators were calculated across the three land use scenarios and the 2017 land use map, which served as a baseline. The quantification and spatial mapping of ecosystem services were performed using InVEST models except for the food production.

Food production

Enset (*Ensete ventricosum*) is among the main home garden food crops in Ethiopia. In the Wabe River catchment, enset is extensively cultivated and plays a vital role in the community's economic and social life (Shank and Ertiro 1996). To quantify and map the production of enset, the pseudostem and plant height within sample plots were measured, and enset home garden spatial features were extracted from satellite imagery. To estimate the existing stock of kocho, sample plots of 10×10 m were laid at each sampling site in the eight transects ranging from 11 to 80 km long from the lower to the higher altitude and located 5 km apart. A household questionnaire survey was administered along with population census data to estimate the local demand of enset crop food (kocho). A total of 120 sample plots were investigated. Suitable models were used to quantify the yield and demand of kocho, and further interpolation, analysis, and mapping were done using the ArcGIS software (Sahle et al. 2018b). Data on the various agroforestry and cereal crop production were obtained from the reports of Central Statistical Agency of Ethiopia (CSA 2017). To estimate the total production of food under each scenario, the area coverage of enset-based agroforestry and cereal crop was multiplied by the average production of each crop type.

Carbon storage and sequestration

Agriculture, forestry, and related land uses are becoming the major contributing factors to climate change. They are responsible for approximately 25% of anthropogenic GHG emissions, mainly from deforestation and agricultural emissions from livestock, soil, and nutrient management (Smith et al. 2014). Thus, the carbon balance within a landscape must be assessed to evaluate the ecosystem service of climate regulation. The amount of carbon sequestered within the landscape during the simulation period was calculated using land use information and data on carbon stocks in three major carbon pools of aboveground and belowground woody biomass, and soil (Sahle et al. 2018a). The above and below ground carbon, and soil carbon pool data, combined with the LULC projection under each scenario, estimates the carbon storage and sequestration potential of each scenario. The InVEST Carbon Storage and Sequestration Model aggregates the amount of carbon stored in each pool according to the LULC maps and table classifications (Sharp et al. 2016). These measures included the total carbon sequestered in the landscape under each scenario. By taking the difference between carbon storage aggregate in the LULC under each scenario from the base LULC, the model measured how carbon sequestration would differ spatially in the LULC scenarios.

Water provision

InVEST biophysical models calculate the amount of water provisioned from each cell in the landscape by calculating the annual amount of rainfall that does not evaporate and determined by the cell vegetation characteristics. The water yield model calculates the average annual water yield in each grid cell using root restricting layer depth (mm), plant available water content, average annual precipitation, average annual potential evapotranspiration, and LULC. Details of the annual water yield model assumption, equation, and work flow were described in the model documentation (Sharp et al. 2016). The required data such as meteorological, soil and hydrological group, DEM, and runoff were gathered from different sources (National Meteorological Services Agency, FAO, Ministry of Water Resources, etc.) and prepared according to the model requirements. To quantify and map the water yield in a spatially explicit manner under each scenario, the modeled land uses were used.

Erosion control

The InVEST sediment delivery model estimates the soil losses, sediment load delivered to the stream and retained by vegetation, and topographic features on an annual time scale. The sediment delivery module is a spatially explicit model working on the spatial resolution of the input DEM raster (Sharp et al. 2016). For each pixel cell of the DEM raster, the model first computes the amount of eroded sediment, then the sediment delivery ratio, which is the

proportion of soil loss actually reaching the catchment outlet. The amount of annual soil loss on pixel is given by the Revised Universal Soil Loss Equation (RUSLE) based on the rainfall erosivity, soil erodibility, slope length gradient, crop management, and support practice factors. Details of how the sediment retention and soil loss quantified and mapped were described in the model documentation (Sharp et al. 2016). The required data such as rainfall, DEM, soil, land cover, and practices management were gathered from different sources and prepared according to the model requirements. To quantify and map the soil loss and sediment retention in a spatially explicit manner under each scenario, the modeled land uses were used.

Results

Changes in land use land cover patterns under different scenarios

Based on 1986 and 2017 LULC, the probability of land use conversion varies (Table 2). From the LULCs, the probabilities of changing the location of built-up areas and woodland were less. However, the forest and shrubland were very dynamic, and the probabilities of changing their location were 41 and 56%, respectively. Only 67% of enset-based agroforestry was stagnant, and the remaining area would be converted to grazing land, cereal crop, and shrubland.

To predict the future conditions of LULC, in addition to the probabilities of changing the land uses, significant

factors that determined the suitability of the location of each land use type were considered. The logistic regression analysis revealed that the location of the land uses was not much affected by physical (elevation and distance to river) and social (distance to towns) factors, rather affected by distance to road, slope, and population (Table 3). All the LULCs except woodland exhibit positive correlation with distance to road indicating that the land use change was dependent on access to road. Similarly, except wetland, the other LULCs exhibited positive correlation with slope. Built-up areas have positive relationship with population, access to road and slope.

A comparison of the actual LULC map for the year 2017 with the CA–Markov-simulated map, based on the Kappa statistics, as well as a comparison of each area of the simulated LULC types with the actual area (Table 4), was used for model validation. The Kappa statistics values (0.89) and an overall accuracy of 90% show that there is good agreement between the predicted result and the actual value of the LULC types for the base year.

The simulation results for 2030 revealed that some of the LULCs such as Afro-alpine and Subafroalpine vegetation, built-up areas, cereal crop, bare land, wetland, and woodland would maintain their trend observed for the period 1986–2017 (Table 4). Forest would decrease by 0.8% from 2017 in the BAU scenario. On the other hand, shrubland increased in 2017 from 1986, and then decreased in the future prediction (Fig. 2).

In the climate-resilient scenario, the Afro-alpine and Subafroalpine vegetation, woodland, enset-based agroforestry, and wetland LULCs area coverage would remain the same as in 2017 (Fig. 2). While the forest, cereal crop,

Table 2 The probabilities of changes between LULC

LULC	Enset-based agroforestry	Cereal crop	Grazing land	Bare land	Shrubland	Forest	Built up	Afro-alpine and Subafroalpine vegetation	Wetland	Woodland
					Probabilities of changing to					
Enset-based agroforestry	0.67	0.13	0.13	0.01	0.06	0	0	0	0	0
Cereal crop	0.09	0.56	0.21	0.08	0.04	0.01	0.01	0	0	0
Grazing land	0.14	0.39	0.37	0.04	0.03	0.01	0	0.02	0	0
Bare land	0.11	0.40	0.05	0.37	0.26	0.10	0	0.01	0	0
Shrubland	0.28	0.05	0.02	0	0.44	0.16	0	0	0	0.04
Forest	0.04	0.08	0.01	0.01	0.25	0.59	0	0.02	0	0
Built up	0	0	0	0	0	0	0.99	0	0	0
Afro-alpine and Subafroalpine vegetation	0.05	0.38	0.18	0.02	0.02	0.01	0	0.35	0	0
Wetland	0.02	0.02	0.04	0	0.01	0	0.02	0	0.9	0
Woodland	0	0	0	0	0.16	0	0	0	0	0.84

Table 3 The logistic regression analysis to determine the suitability of the location of each land use types

Variables	Enset-based agroforestry	Cereal crop	Grazing land	Bare land	Shrub land	Forest	Built up	Afro-alpine and Subafroalpine vegetation	Wetland	Woodland
Constant	11.66	10.72	10.47	9.14	11.66	10.92	24.24	6.75	13.90	14.25
Elevation	− 0.26	− 0.09	− 0.10	− 0.22	− 0.35	− 0.30	− 0.11	− 0.08	− 0.20	− 3.09
Population	− 0.27	− 0.33	− 0.23	− 0.21	− 0.42	− 0.45	0.58	− 1.24	− 1.95	− 1.51
Dist. to river	− 0.53	− 0.42	− 0.46	− 0.51	− 0.63	− 0.65	0.00	0.11	− 0.66	− 0.44
Dist. to road	0.04	0.06	0.03	0.09	0.09	0.06	0.34	0.43	1.31	0.15
Dist. to town	− 0.30	− 0.13	− 0.19	− 0.16	− 0.32	− 0.37	− 20.65	− 0.59	− 4.84	0.21
Slope class	0.22	0.13	0.15	0.19	0.41	0.55	0.19	0.14	− 0.06	0.50

Table 4 The LULC in the past, present, and at different scenarios (% of landscape) in the Wabe River catchment

LULC	1986	2017	2030		
			BAU	Climate resilient	Agroforestry
Afro-alpine and Subafroalpine vegetation	4.8	2.5	2.4	2.5	2.5
Forest	11.3	9.3	8.5	11.7	9.3
Woodland	2.2	2.1	2.1	2.1	2.1
Shrubland	7.6	12.4	10.7	12.2	12.5
Enset-based agroforestry	16.9	17.6	18.3	17.9	50
Grazing land	25.1	19.4	19.4	19	19
Wetland	0.2	0.2	0.2	0.2	0.2
Cereal crop	27.1	32.5	34	33.8	0
Built up	0.1	0.4	0.8	0.8	0.8
Bareland	5	3.7	3.3	0.3	3.7

and built-up LULCs area would increase by a small percentage, and the bare land area would decrease (Table 4).

The agroforestry-focused scenario result shows that large change would occur in the enset-based agroforestry and cereal crop LULCs. The whole area of the cereal crop would be transformed into enset-based agroforestry, making 50% of the catchment area to be covered with this LULC (Table 4 and Fig. 2). The built-up area would be double compared to the 2017 baseline.

Ecosystem services and their changes under different scenarios

Food production

According to CSA (2017), the average cereal crop production including teff (*Eragrostis tef*), barley, maize, beans, and peas of Gurage zone was 2.5 tons/ha. From the home garden, 6.4 tons of Ethiopian cabbage, 12 tons of potato and carrot, 1.2 tons of khat (*Catha edulis*), 0.2 tons of coffee, and 10.2 tons of fruits (such as avocado, papaya,

and mango) are produced per hectare. The average annual kocho production from enset crop was 6.5 tons/ha. Thus, the average home garden and enset-based agroforestry crop production could be 6.9 tons/ha.

As the result of decrease in area coverage of enset-based agroforestry in the BAU scenario, the total yield of food production decreased by 0.6% from the baseline, even though the cereal crop production was increased by 4.9% (Table 5). In the climate scenario, due to a strategic plan to enhance the productivity of cereal crop to 3 tons/ha, the food production will be increased by 31% from the baseline. Whereas in the agroforestry scenario, as a result of the high increment of enset-based agroforestry at the expense of cereal crop, the food production would increase by 102.9% from the baseline yield (Figs. 3, 5).

Carbon storage and sequestration

The results of the baseline carbon stock estimation revealed that, among the LULCs, the Afro-alpine and Subafroalpine vegetation cover exhibited the highest average total carbon

Table 5 Food production at different scenario (tons) in the Wabe River catchment

LULC	Baseline	BAU	%	Climate resilient	%	Agroforestry	%
Enset-based agroforestry	225,520	223,332	− 1	224,657	− 0.4	640,541	184.0
Cereal crop	151,063	158,530	4.9	188,835	25.0	0	− 100.0
Total	315,617	313,617	− 0.6	413,492	31.0	640,541	102.9
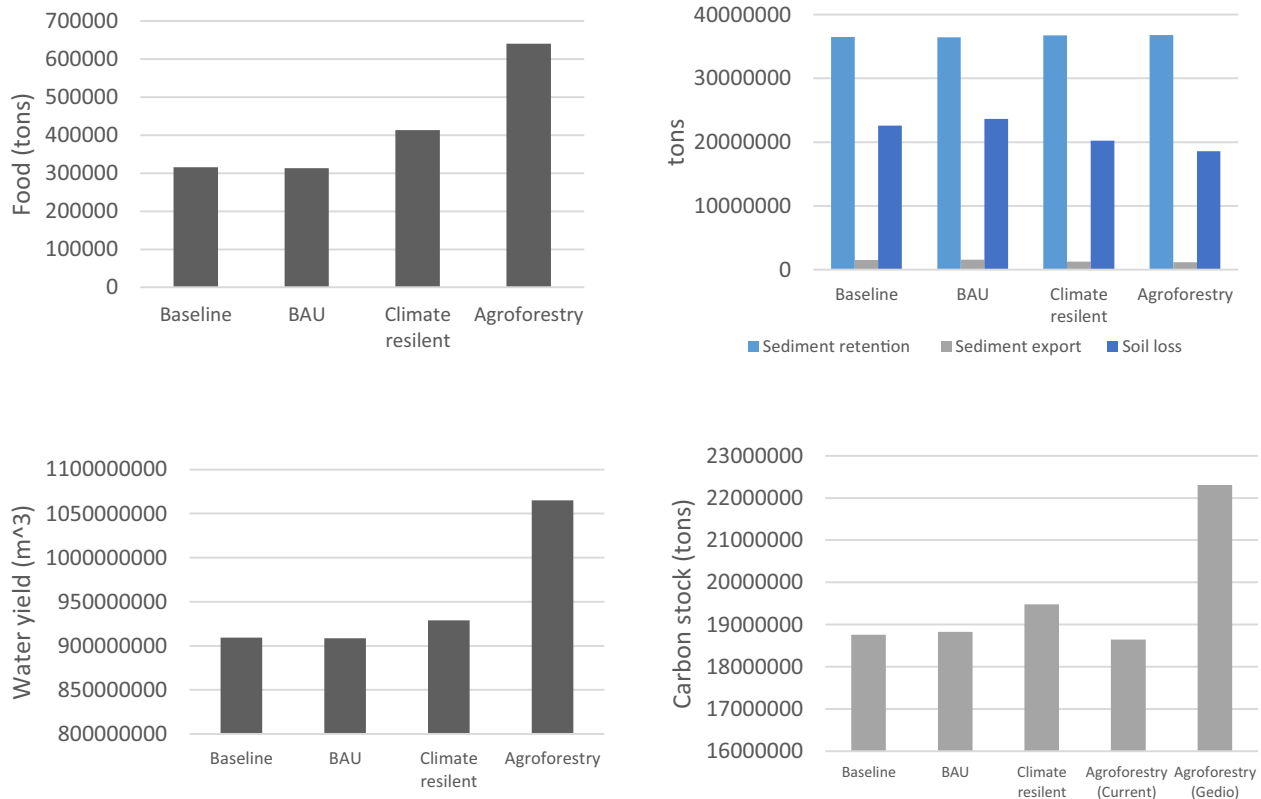
Fig. 3 The trends of ecosystem services at different scenarios in the Wabe River catchment

stock of 175 ± 78 tons/ha mainly because of the highest soil organic carbon. Forest land exhibited the second-largest carbon stock (109 ± 104 tons/ha) with the combination of the highest woody biomass and soil organic carbon. Woodland, cereal crop, and enset-based agroforestry, exhibiting an almost similar carbon stock, were ranked as the third highest. Bare land and built-up areas exhibited the lowest carbon stock, with 72 ± 11 and 70 ± 0.5 tons/ha, respectively. The total amount of carbon stock in the catchment was 18,691,500 tons and can offset 68,597,700 tons of CO_2-eq. GHG. On account of its larger area coverage, crop land exhibited the largest stock.

Based on the current average estimation of carbon in the Wabe River catchment, the highest carbon stock change was observed in the climate-resilient scenario (3.8% increase from the baseline) since there are several

management activities in this scenario. Compared to the baseline, carbon stock would decrease in the BAU scenario by 0.4%. But in the agroforestry scenario, the carbon stock amount decreased by 0.6% from the baseline since the average carbon stock in enset-based agroforestry is less than cereal crop. However, according to Mesele and Starr (2013), the average stock of carbon in Gedeo agroforestry system in Southern Ethiopia ranged from 133 to 179 tons/ha. Since the assumption of this study on agroforestry scenario was to establish such a type of agroforestry system, when we consider the minimum average carbon stock of this system (133 tons/ha), the agroforestry scenario result increased by 18.9% from the baseline. In total, the Wabe River catchment could store 22,308,810 tons of carbon stock under the agroforestry scenario, and 19,478,004 tons in climate-resilient scenario (Figs. 3, 5).

Water provision

The baseline water provision result revealed that precipitation varies across the sub-watersheds from 12,347 to 15,263 m³/ha, and the highest was observed in the upper catchment sub-watersheds. At the same time, the actual evapotranspiration (AET) was highest in the lower tip of the catchment sub-watershed (8636 m³/ha) where Gibe Valley exists. The renewable water yield from precipitation and base flow in the catchment was highest in the upper part of the catchment (Fig. 4). The top mountain sub-watersheds exhibit the highest annual water yield with the maximum mean of 6301 m³/ha. The lowest water yield of < 4000 m³/ha was estimated in three sub-watersheds. In total, the annual water yield of the catchment is 896,296,886 m³.

The results of the water yield at different scenarios showed that, except in the BAU, the volume of water increased from the baseline. The climate and agroforestry scenario water yield was increased from the baseline by 2.2 and 17.1%, respectively. At the same time in the BAU scenario, the water yield decreased by a small amount (0.1% from the baseline).

Erosion control

The baseline result revealed that Wabe River catchment had high an annual soil loss rate of 22.6 metric tons, and annually 201–357 tons/ha soil was lost. The results of the difference in the amount of sediment delivered by the current watershed and a hypothetical watershed where all land cover types have been cleared to bare soil show that 38.6 metric tons of sediments were retained. From the 32 sub-watersheds in the Wabe River catchment (Fig. 4), seven of them retained sediments above 400 tons/ha. Annually, around two metric tons of sediments were exported to streams in the Wabe River catchment. Large parts of upper catchment sub-watersheds had an annual sediment export range from 10 to 20 tons/ha. Lower catchment sub-watershed areas had low sediment export (less than five tons/ha).

The results of soil erosion control status at different scenarios revealed that the sediment export and soil erosion increased in the BAU from the baseline by 4.8 and 4.7%, respectively (Table 6). On the other hand, the sediment retention decreased by 0.2%. From the three scenarios, the highest increase in sediment retention and decrease in
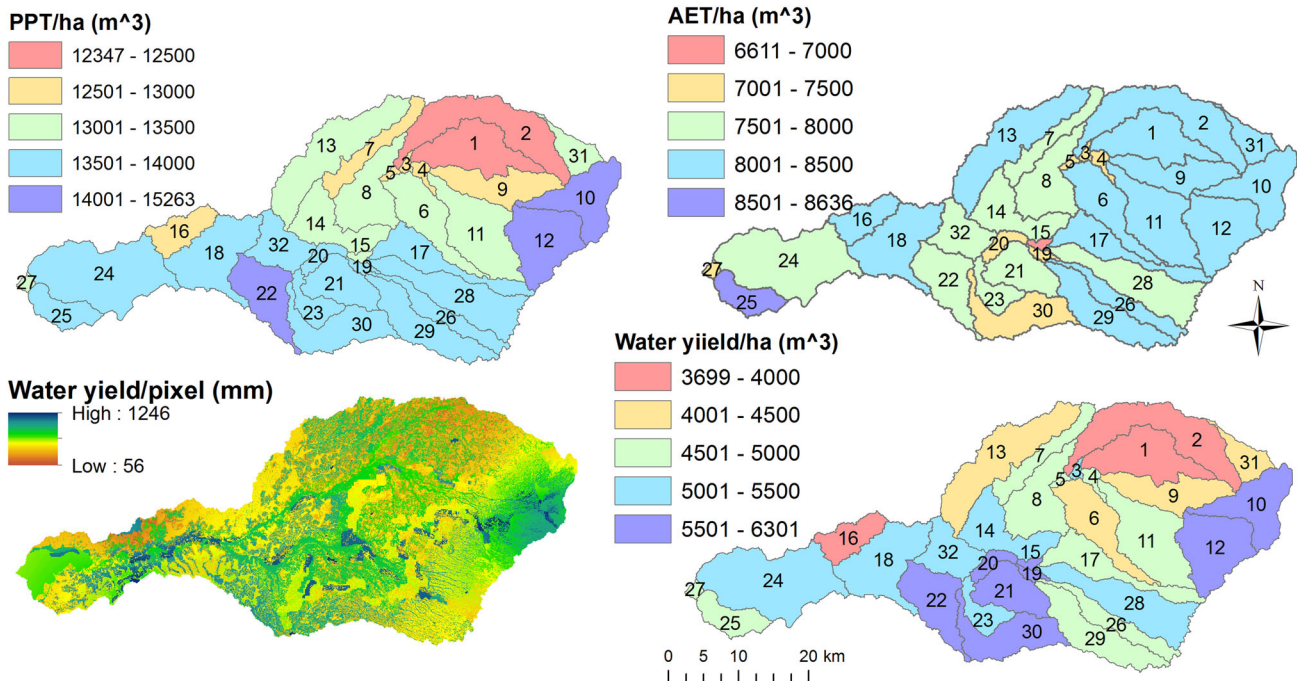

Fig. 4 The annual precipitation, AET, and water yields of Wabe River catchment

Table 6 Sediment retention, sediment export, and soil loss at different scenarios (metric tons) in the Wabe River catchment

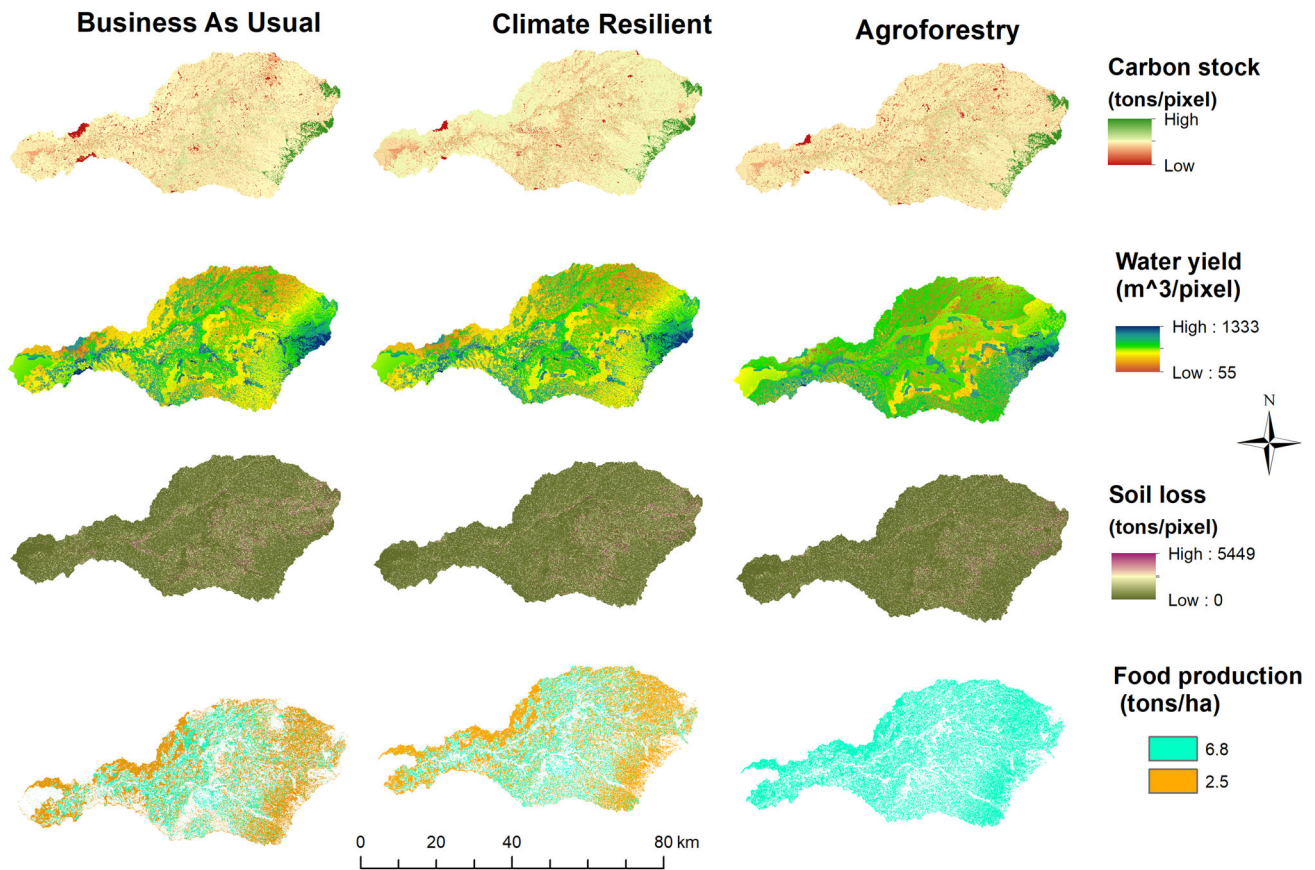| Ecosystem services	Baseline	BAU	%	Climate resilient	%	Agroforestry	%
Sediment retention	36.5	36.4	− 0.2	36.7	0.7	36.8	0.9
Sediment export	1.5	1.6	4.8	1.3	− 14.6	1.9	− 21.0
Soil loss	22.6	23.6	4.7	20.2	− 10.4	18.6	− 17.7

Fig. 5 The quantified ecosystem services in different scenarios in the Wabe River catchment

sediment export and soil erosion were exhibited in the agroforestry scenario (Figs. 4, 5). In this scenario, the sediment export and soil loss decreased by 21 and 17.7%, respectively, and sediment retention increased by 0.9% (Table 6). Compared to the baseline in the climate-resilient scenario, the sediment retention increased, and the sediment export and soil erosion decreased, even though the percent of increases and decreases were less than the agroforestry scenario.

Synergy and tradeoffs between ecosystem services

The quantification and mapping of ecosystem services in the Wabe River catchment revealed that all of the ecosystem services exhibited synergies between the modeled scenarios. As Fig. 6 shows, in the climate-resilient and agroforestry scenario, food production, carbon stock, and water yield increase while soil losses decrease. On the contrary, soil loss increased and the other ecosystem services decreased in the BAU. In climate scenario, all of the quantified regulating and provisioning services, except soil loss, were increased even though a high increase was exhibited in climate regulation (carbon sequestration).
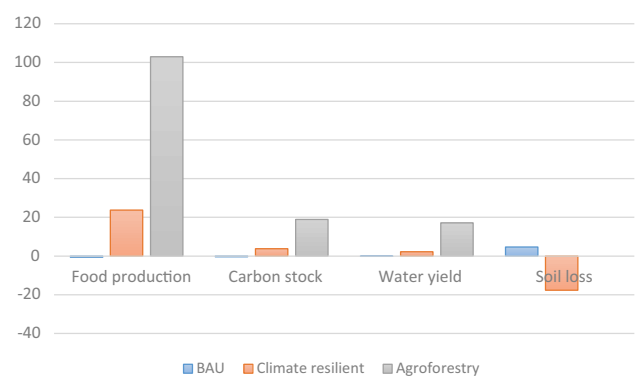

Fig. 6 Synergies and tradeoffs between ecosystem services at different scenarios (% of change) in the Wabe River catchment

Thus, the land use management activities to produce climate-resilient green economy in Ethiopia could also contribute to the increase in the provisions of the other ecosystem services, and exhibited good synergy with other services. From the three scenarios, an increase in the provision of ecosystem services, except sediment retention, was observed in the agroforestry scenario. The food production increased by 102.9% and the other services increased by more than 10%.

Discussion

Land use scenario modeling and validation

Understanding the future LULC patterns of Ethiopia's development strategy and other scenarios using a modeling approach is important for decision makers to evaluate the impacts of the strategy before the end of the target period. In this study, using LULC and their associated driver datasets, we successfully simulated the LULCs patterns and dynamics for the next 13 years in the Wabe River catchment of Gurage Mountain chain in Ethiopia using future modeling tools of Land Change Modeler for ArcGIS (LCM) and InVEST Scenario Generator model. Three kinds of scenarios, i.e., BAU, climate resilient, and agroforestry, were designed.

The LCM can depict the direction of LULC shifts and predict the future land requirements for land use categories by taking into account the influence of related factors on land use requirements. The methodology is effective and realistic for predicting possible LULC changes under different scenarios and for providing a scientific basis for land use decision making and planning (Han et al. 2015). The recent validation studies have indicated that most spatial models still contain a high level of uncertainty (Pontius et al. 2004). Since the simulation of this study, future LULC patterns based on the past trends and the 1986 and 2017 LULCs were classified with an overall accuracy of 91.6 and 88.4%, respectively, and the uncertainty of the future prediction decreased. The accuracy level in the BAU scenario (90%) is within the range of accuracies found in previous similar simulation studies (Echeverria et al. 2008; Kamusoko et al. 2011). The interpretation of these high values is that the majority of the study area experienced no change.

To design the climate-resilient and agroforestry scenarios, the InVEST Scenario Generator tool was used to build the relative likelihood of one LULC changing into another in 2030. Using spatially explicit data from the 2017 LULC and the likelihood of change as defined by the matrices, the InVEST Scenario Generator modeled how the 2017 LULC could change under the exhibited scenarios. Recently, this scenario generator tool was used in various LULC scenario models (Sharp et al. 2016; Gibson and Quinn 2017).

LULC changes in the Wabe River catchment

The simulation results based on the past trends for 2030 revealed that the vegetation covered LULCs such as Afro-alpine and Subafroalpine vegetation, forest, wetland, and woodland decreased, while built-up areas, enset-based agroforestry and cereal crop increased. Studies on the future modeling of land uses in Ethiopia show that an increase in agricultural land, at the expense of vegetation cover, was common (Yalew et al. 2016; Yirsaw et al. 2017; Kindu et al. 2017).

The past trends of land use changes in the Wabe River catchment could be due to the indirect drivers such as demographic changes, economic activities, poverty, policy and institutional changes, and the indirect drivers such as improper agricultural practices, climate variability and change, and demand for firewood and construction materials. Human population increases in the Wabe River catchment obliged farmers to farm every piece of land continuously without fallow. Land shortage pushed farmers to convert forests, shrubs and Afro-alpine and Sub-afroalpine vegetation covers on their own land into crop land. Poverty is one of the causes for LULC dynamics and land degradation in the Ethiopian highlands (Wubie et al. 2016). People with low income, who cannot meet their subsistence needs by purchasing needed food items, are forced to use common resources, such as forests for fuel, pastures for fodder, and ponds and rivers for water. Households in the catchment use forests and shrubs as sources of income for living by selling firewood, charcoal, and poles for construction. In addition, due to lack of purchasing power, agricultural inputs such as fertilizer, improved seeds and cultivating their small land every year, there is a loss of land fertility. Thus, farmers are forced to find new land to farm and/or graze their livestock by converting other land uses. Currently, common grazing land is being converted to agricultural land, due to a shortage of farm land. This land was, especially, given to the organized youth in the community by the government. Overexploitation of timber for marketable products, such as firewood and construction materials, has greatly increased pressure on these forest ecosystems. The problem in the Wabe River catchment related to fuel wood and construction materials was not only clearing forest and shrub land to satisfy their demand, but also for the plantation of eucalyptus trees for construction materials and firewood on cleared vegetation areas, and on crop and grazing land to sell.

Ecosystem services and their changes under different scenarios

This study shows that in the BAU, the area coverage of ecologically high value land covers were decreased, resulting in a decrease in the provisioning and regulating services. The trend shows that food production could decrease since the degradation of ecologically important landscape could also contribute for decrease in food production. The decrease in the value of ecosystems, except

for food production, was similar to the modeling studies in other landscapes of Ethiopia (Yalew et al. 2016; Yirsaw et al. 2017; Kindu et al. 2017).

The LULC patterns and changes under the BAU scenarios in the studied catchment have different limitations and hindering factors. In this scenario, communities may continue with the usual manner of subsistence agriculture by exploiting the existing natural resources. For example, expansion of croplands and grasslands has been enacted at the expense of Afro-alpine and Subafroalpine vegetation, natural forests and shrubland. Such kinds of change in the LULC, however, will negatively alter the potential use of an area and may ultimately lead to loss of productivity (Tegene 2002; Kindu et al. 2017). This could, in turn, affect the communities by reducing the means of livelihoods of those who depend on land. This study BAU scenario result confirms that food production decrease. Other limitation associated with the expansion of agricultural land at the expense of the natural ecosystem is the decline in biodiversity (Kindu et al. 2017). The study catchment has numbers of high value index species that range from dry lands to Afro-alpine and Subafroalpine vegetation, some of which require high conservation priority (Sahle et al. 2018c). In addition, the high capacity of carbon storage and sequestration of the socio-ecological environment will decline as the current changes in LULC in the catchment results for CO_2 emissions were greater than the carbon sequestration rate (Sahle et al. 2018a). Furthermore, expansion of croplands towards marginal lands on steep and very steep slopes will cause more runoff, will accelerate the soil erosion, may decrease water supplies, and could finally lead to land degradation (Tegene 2002; Lemenih and Teketay 2004; Kindu et al. 2017).

The climate-resilient scenario exhibited a large enhancement in the examined ecosystem services in addition to carbon storage and sequestration services. This, as a result of the strategies taken to reduce GHG emissions, could also contribute to the enhancement of other services. Intensifying agriculture through usage of improved inputs, better residue management, and creating new agricultural land in degraded areas to reduce the pressure on forests could contribute to enhance food production in addition to reducing GHG emissions. The measures taken to protect and re-establish forests to reduce GHG emissions could also: provide protection for soil and water resources by controlling the discharge of water into streams and rivers, preserve biodiversity, boost land fertility, and increase water infiltration to replenish aquifers. As a result, in the climate-resilient scenario, carbon stock, food production, water provision, and sediment retention were enhanced, and the soil erosion was decreased compared to the baseline and the BAU land use managements.

The major constraint associated with the climate-resilient scenario is the investment capital. Since the majority of the listed management activities considered in this scenario needs technological adaptation, the costs of implementation are high. For instance, usage of improved inputs and better residue management, small-, medium-, and large-scale irrigation, increase animal value chain efficiency including productivity, mechanized draft power, dissemination and usage of fuel-efficient stoves and/or alternative-fuel cooking and baking techniques, and area closure required large amounts of capital. This could hinder the implementation, even though the scenario provides a holistic approach to land use management.

The agroforestry scenario performs economically and ecologically best because the high productivity of this agroforestry system helps the community to improve food security, regulate climate change, enhance soil fertility, reduce erosion and improve water quality (Mulugeta and Mabrate 2017). The agroforestry advantages of the study area are due to the provision of multiple products (food, fruit, vegetables, fodder, spices, medicines, oils, nuts, fibers, fuel wood, and timber) which can also generate income—especially for smallholders (Bishwa 2003). The high yields of an indigenous crop of enset substituting the common cereal crops, which can be grown on a small plot of land, could support the food demand of households (Mulugeta and Mabrate 2017). Enset farming systems contribute to the long-term sustainability of food production because enset can be stored for long periods, can be harvested at any time during the year, can be harvested at any stage over a period of several years, and can survive high-stress years that reduce other food sources (Brandt et al. 1997). The enset main food (Kocho) has high energy value with 6.5 MJ per kg (Wolde-Gebriel et al. 2006). The production of fruits and vegetables for consumption and sale at the local market is another important advantage of food production in the system. Coffee and khat are cash crops integrated in the system which are the main export items of Ethiopia.

The traditional agroforestry system in many regions has shown great value in maintaining a high degree of diversity (UNU-IAS & IR3S, UTIAS 2016). The diversity of plants in the home garden, associated with other organisms, contributes to the formation and maintenance of soil structure and the retention of moisture and nutrient levels and promotes the recycling of nutrients (Verchot et al. 2007). This is particularly important in hillside farming, where agriculture may lead to rapid loss of soil. As a result, the intact vegetation cover incidences of runoff and erosion can be minimal (Kanshie 2002; Badege et al. 2013). The hydrology of the system is well maintained and enhanced by reduced evapotranspiration due to its canopy structure and pumping effect of trees (Bogale 2007). Carbon stocks

in a well-established system of agroforestry, such as Gedeo, are among the highest reported for tropical forests and agroforestry systems (Mesele and Starr 2013). The higher soil carbon stocks in such systems can be attributed to the higher proportion of trees and associated coarse litter and humus inputs. Thus, establishment of such a type of ecological landscape in the catchment could exhibit best ecological services—even better than the climate-resilient development strategies of Ethiopia.

Attempting only strict implementation of an agroforestry scenario will decrease cereal crop lands by 100%, which forces the low income farmers to purchase cereal crops in the market. In recent times, under pressure from land fragmentation and environmental and societal change, many Ethiopian smallholders are in the process of transforming their farming strategy towards market-oriented monocropping to meet their needs for household food security and income (UNU-IAS & IR3S, UTIAS 2016). This attitude may lead farmers to resist conversion of the total cereal crop lands into an enset-based agroforestry system, and could hinder the implementation of this scenario in the catchment. However, the expansion of enset-based agroforestry in the catchment could enhance multiple benefits in the community.

The current land use change factors (stated in Sect. 4.2) could affect the developed land use scenarios although their impact varies. In the BAU scenario, all the factors could continually affect the land use change since the trends will be continued. In climate-resilient and agroforestry scenarios, even though the cause for land use changes such as demographic change continues, the climate-resilient activities and the agroforestry system establishment could changes some of the economic activities. These activities could reduce the prospective of the causes to change the land use.

Conclusions

In this study, we simulated the LULC patterns for the year 2030 in the Wabe River catchment of the Gurage Mountain chain in Ethiopia using the future modeling tools LCM and InVEST Scenario Generator model. From the three future scenarios, food production, carbon stock and water provision were very high in the agroforestry scenario as well as in the climate-resilient scenario, while sediment retention was very high in the climate-resilient scenario. In the BAU scenario, the ecosystem services considered herein, including food production, were decreased from the current status. In the climate-resilient and agroforestry scenarios, all of the quantified ecosystem services were increased through synergies. Thus, implementing the climate-resilient strategy of Ethiopia could enhance the existing

provisions of ecosystem services. Meanwhile, expansion of an enset-based agroforestry system in the Wabe River catchment is the best land use management to ensure sustainable food production while conserving the environment. Thus, planners and decision makers should use this study information to include enset-based agroforestry expansion in the strategy, and to implement it before the end of the strategy period. While implementing this type of land use in the catchment and in similar parts of the regions, further studies are needed for adoption of the agroforestry system according to agro-ecological zones. In this study, by understanding the local context of the landscape, we explored the best approach of agroforestry system land use management, especially for developing countries. Thus, we suggest that land use planners should think over their planning areas before they start developing strategies.

References

Badege B, Neufeldt H, Mowo J, Abdelkadir A, Muriuki J, Dalle G, Assefa T, Guillozet K, Kassa H, Dawson IK, Luedeling E, Mbow C (2013) Farmers' strategies for adapting to and mitigating climate variability and change through agroforestry in Ethiopia and Kenya. In: Davis CM, Bernart B, Dmitriev A (eds) Forestry communications group. Oregon State University, Corvallis

Bishwa NR (2003) Contribution of agroforestry for rural livelihoods: A case of Dhading District, Nepal. The International Conference on Rural Livelihoods, Forests and Biodiversity 19–23 May 2003, Bonn, Germany

Bogale T (2007) Agroforestry practice in gedeo zone, Ethiopia: a geographical analysis. PhD dissertation nr. 188. Punjab University, India

Brandt SA, Spring A, Hiebsch C, McCabe JT, Tabogie E, Diro M, Wolde-Michael G, Yntiso G, Shigeta M, Tesfaye S (1997) The "tree against hunger": Enset-based agricultural system in Ethiopia. American Association for the Advancement of Science, Washington, D.C.

Brown S, Grais A, Ambagis S, Pearson T (2012) Baseline GHG emissions from the agricultural sector and mitigation potential in countries of East and West Africa. CCAFS Working Paper 13. CCAFS, Copenhagen, Denmark

Central Intelligence Agency (CIA) (2018) World factbook and other sources. https://theodora.com/wfbcurrent/ethiopia/ethiopia_economy.html. Accessed 6 May 2018

CRGE (Climate Resilient Green Economy) (2011) Ethiopia's green economy strategy. Federal Democratic Republic of Ethiopia, Addis Ababa

CSA (Central Statistical Agency) (2017) Agricultural sample surveys 2016/17 Report on area and production of major crops. Statistical bulletin 584, Addis Ababa

Díaz S, Pascual U, Stenseke M, Martín-López B, Shirayama Y (2018) Assessing nature's contributions to people. Science 359(6373):270–272. https://doi.org/10.1126/science.aap8826

Eastman JR (2006) IDRISI Andes Tutorial. Clark University, Worcester, USA, Clark labs

Echeverria C, Coomes DA, Hall M, Newton AC (2008) Spatially explicit models to analyze forest loss and fragmentation between 1976 and 2020 in southern Chile. Ecol Model 212(3–4):439–449. https://doi.org/10.1016/j.ecolmodel.2007.10.045

Ellis E, Pontius R (2007) Land-use and land-cover change. In: Cutler J (ed) Encyclopedia of Earth. Springer, Washington

Estoque RC, Murayama Y (2012) Examining the potential impact of land use/cover changes on the ecosystem services of Baguio city, the Philippines: a scenario- based analysis. Appl Geogr 35(1–2):316–326. https://doi.org/10.1016/j.apgeog.2012.08.006

Foley JA, De Fries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz J, Prentice IC, Ramankutty N, Snyder PK (2005) Global consequences of land use. Science 309(5734):570–574. https://doi.org/10.1126/science.1111772

Fürst C, Helming K, Lorz C, Müller F, Verburg PH (2013) Integrated land use and regional resource management—a cross-disciplinary dialogue on future perspectives for a sustainable development of regional resources. J Environ Manag 127(Supplement):S1–S5. https://doi.org/10.1016/j.jenvman.2012.12.015

Geneletti D (2013) Assessing the impact of alternative land-use zoning policies on future ecosystem services. Environ Impact Assess Rev 40:25–35. https://doi.org/10.1016/j.eiar.2012.12.003

Gibson D, Quinn J (2017) Application of anthromes to frame scenario planning for landscape- scale conservation decision making. Land 6(2):33. https://doi.org/10.3390/land6020033

Han H, Yang C, Song J (2015) Scenario simulation and the prediction of land use and land cover change in Beijing China. Sustainability 7(4):4260–4279. https://doi.org/10.3390/su7044260

IGBP (The International Geosphere-Biosphere Programme) (1999) Land use and land cover change (LUCC) Implementation Strategy. IGBP Report No. 48/IHDP Report No 10. Stockholm, Sweden

IPBES (2016) Summary for policymakers of the methodological assessment of scenarios and models of biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In: Ferrier S, Ninan KN, Leadley P, Alkemade R, Acosta LA, Akçakaya HR, Brotons L, Cheung W, Christensen V, Harhash KA, Kabubo-Mariara J, Lundquist C, Obersteiner M, Pereira H, Peterson G, Pichs-Madruga R, Ravindranath NH, Rondinini C, Wintle B (eds) Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany

Kamusoko C, Oono K, Nakazawa A, Wada Y, Nakada R, Hosokawa T, Tomimura S, Furuya T, Iwata A, Moriike H, Someya T, Yamase T, Nasu M, Gomi Y, Sano T, Isobe T, Homsysavath K (2011) Spatial simulation modelling of future forest cover change scenarios in Luangprabang Province. Lao PDR. Forests 2(3):707–729. https://doi.org/10.3390/f2030707

Kanshie TK (2002) Five thousand years of sustainability? a case study on Gedeo land use (Southern Ethiopia). Thesis Wageningen University, The Netherlands

Kindu M, Thomas S, Martin D, Demel T, Thomas K (2017) Scenario modelling of land use/land cover changes in Munessa-Shashemene landscape of the Ethiopian highlands. Sci Total Environ 622–623:534–546. https://doi.org/10.1016/j.scitotenv.2017.11.338

Lemenih M, Teketay D (2004) Restoration of native forest flora in the degraded highlands of Ethiopia: constraints and opportunities. SINET 27:75–90

Mesele N, Starr M (2013) Litter-fall production and associated carbon and nitrogen fluxes of seven woody species grown in indigenous agroforestry systems in the Rift Valley escarpment of Ethiopia. Nutr Cycl Agroecosyst 97(1–3):29–41. https://doi.org/10.1007/s10705-013-9590-9

Mulugeta G, Mabrate A (2017) Production and ecological potentials of Gedeo's indigenous agroforestry practices in Southern Ethiopia. J Resour Dev Manag 30. ISSN 2422-8397

National Metrological Services Agency (NMA) (2016) Climate data. National Metrological Services Agency, Addis Ababa

Odindi J, Mhangara P, Kakembo V (2012) Remote sensing land-cover change in Port Elizabeth during South Africa's democratic transition. S Afr J Sci 108(5/6):1–7. https://doi.org/10.4102/sajs.v108i5/6.886

Pereira HM, Navarro LM, Martins IS (2012) Global biodiversity change: the bad, the good, and the unknown. Annu Rev Environ Resour 37:25–50

Petz K, van Oudenhoven APE (2012) Modelling land management effects on ecosystem functions and services: a study in The Netherlands. Int J Biodivers Sci Ecosyst Serv Manag 8(1–2):135–155. https://doi.org/10.1080/21513732.2011.642409

Pontius RG, Huffaker D, Denman K (2004) Useful techniques of validation for spatially explicit land-change models. Ecol Model 179(1):445–461. https://doi.org/10.1016/j.ecolmodel.2004.05.010

Reid RS, Kruska RL, Muthui N, Taye A, Wotton S, Wilson CJ, Mulatu W (2000) Land–use and land–cover dynamics in response to changes in climatic, biological and socio–political forces: the case of south western Ethiopia. Landscape Ecol 15(4):339–355. https://doi.org/10.1023/A:1008177712995

Sahle M, Saito O, Fürst C, Yeshitela K (2018a) Quantification and mapping of the supply of and demand for carbon storage and sequestration service in woody biomass and soil to mitigate climate change in the socio-ecological environment. Sci Total Environ 624:342–354. https://doi.org/10.1016/j.scitotenv.2017.12.033

Sahle M, Yeshitela K, Saito O (2018b) Mapping the supply and demand of enset crop to improve food security in Southern Ethiopia. Agron Sustain Dev 38:7. https://doi.org/10.1007/s13593-017-0484-0

Sahle M, Fürst C, Yeshitela K (2018c) Plant diversity analysis for conservation of Afromontane vegetation in socio-ecological mountain landscape of gurage, south central Ethiopia. IJBC 10(4):161–171. https://doi.org/10.5897/IJBC2017.1172

Shank R, Ertiro C (1996) A linear model for predicting Enset plant yield and assessment of kocho production in Ethiopia. United Nations Development Programme Emergencies Unit for Ethiopia, Addis Ababa, Ethiopia. http://www.africa.upenn.edu/eue_web/enset96.htm. Accessed Dec 2016

Sharp R, Tallis HT, Ricketts T, Guerry AD, Wood SA, Chaplin-Kramer R, Nelson E, Ennaanay D, Wolny S, Olwero N, Vigerstol K, Pennington D, Mendoza G, Aukema J, Foster J, Forrest J, Cameron D, Arkema K, Lonsdorf E, Kennedy C, Verutes G, Kim CK, Guannel G, Papenfus M, Toft J, Marsik M, Bernhardt J, Griffin R, Glowinski K, Chaumont N, Perelman A, Lacayo M Mandle L, Hamel P, Vogl AL, Rogers L, Bierbower W, Denu D, Douglass J (2016) InVEST +VERSION+ User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund

Shoyama K, Yamagata Y (2014) Predicting land-use change for biodiversity conservation and climate-change mitigation and its

effect on ecosystem services in a watershed in Japan. Ecosyst Serv 8:25–34. https://doi.org/10.1016/j.ecoser.2014.02.004

Slonecker ET, Barnes Christopher, Karstensen, Krista, Milheim LE, Roig-Silva CM (2013) Consequences of land use and land cover change: U.S. Geological Survey Fact Sheet 2013–3010. https://pubs.usgs.gov/fs/2013/3010/

Smith P, Bustamante M, Ahammad H, Clark H, Dong H, Elsiddig EA, Haberl H, Harper R, House J, Jafari M, Masera O, Mbow C, Ravindranath NH, Rice CW, Abad CR, Romanovskaya A, Sperling F, Tubiello F (2014) Agriculture, forestry and other land use (AFOLU). In: climate change 2014: mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Tegene B (2002) Land-cover/land-use changes in the Derekolli catchment of the South Wello zone of Amhara Region, Ethiopia. East Afr Soc Sci Res Rev 18:1–20. https://doi.org/10.1353/eas.2002.0005

UN-DESA (United Nations Department of Economic and Social Affairs) (2012) A guidebook to the green economy issue 1: green economy, green growth, and low-carbon development—history, definitions and a guide to recent publications. United Nations

UNU-IAS & IR3S, UTIAS (2016) Socio-ecological production landscapes and seascapes (SEPLS) in Africa. United Nations University Institute for the Advanced Study of Sustainability, Tokyo, pp 28–36

Verchot LV, Noordwijk M, Kandji S, Tomich T, Ong C, Albrecht A, Mackensen J, Bantilan C, Anupama KV, Palm C (2007) Climate change: linking adaptation and mitigation through agroforestry. Mitig Adapt Strat G 12(5):901–918. https://doi.org/10.1007/s11027-007-9105-6

Verheye HW (2009) Land use, land cover and soil sciences—Vol. IV. Land Use Management Encyclopedia of Life Support Systems (EOLSS), UNESCO, Oxford

Wolde-Gebriel Z, Pijls LT, Timmer AM, West CE (2006) Review on cultivation, preparation and consumption of Ensete (*Ensete ventricosum*) in Ethiopia. J Sci Food Agric 67:1–11. https://doi.org/10.1002/jsfa.2740670102

Woldetsadik M (2003) Impacts of population pressure on land use/land cover change, agricultural system and income diversification in West Gurageland, Ethiopia. PhD Thesis, Department of Geography, Faculty of Social Sciences and Technology Management, Norwegian University of Science and Technology, NTNU, Trondheim. ISBN 82;471:5230– 5234

Wubie MA, Assen M, Nicolau MD (2016) Patterns, causes and consequences of land use/cover dynamics in the Gumara watershed of Lake Tana basin, north western Ethiopia. Environ Syst Res 5:8. https://doi.org/10.1186/s40068-016-0058-1

Yalew S, Mul ML, van Griensven A, Teferi E, Priess J, Schweitzer C, van Der Zaag P (2016) Land-use change modelling in the Upper Blue Nile Basin. Environments 3:21. https://doi.org/10.3390/environments3030021

Yirsaw E, Wu W, Shi X, Temesgen H, Bekele B (2017) land use/land cover change modeling and the prediction of subsequent changes in ecosystem service values in a coastal area of China, the Su-Xi-Chang region. Sustainability 9:1204. https://doi.org/10.3390/su9071204