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Impact of Landscape Management Scenarios on Ecosystem Service Values in Central Ethiopia

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Abstract: This study aimed at modeling scenarios of future land use and land cover (LULC) change and estimating ecosystem service (ES) values for the year 2051 compared to 2021 in Central Ethiopia. The future LULC changes for the year 2051 were simulated for four scenarios, namely Business-as-Usual (BAU), Rapid Agricultural Expansion (RAE), Ecosystems Protection and Agricultural Development (EPAD) and Landscape Ecosystems Restoration and Conservation (LERC). The four LULC change scenarios were simulated based on anticipated assumptions that were derived from existing spatial policies, a consultation workshop report on scenarios of agricultural development in Ethiopia, suitability analysis, population growth analysis and expert knowledge of the study area characteristics. We used a Multi-Layer Perceptron–Artificial Neuron Network (MLP–ANN) model-based projected LULC for the BAU scenario and the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model to generate RAE, EPAD and LERC scenarios in the study landscape. The benefit transfer method was used to estimate the total ES values and for trade-off analysis. The result showed that LULC changes in the study area varied across simulated scenarios compared to the base year 2021. Under the BAU and RAE scenarios, cultivated land increased by 146,548 ha (22%) and 193,965 ha (29%), whereas forest, water body, wetland and shrub-bush land were reduced. However, forest cover increased by 31,725 ha and 100,080 ha but bare land was reduced by 8466 ha (21%) and 10,379 ha (25%) under the EPAD and LERC scenarios. The forest cover annual rate of change was 3.2% and 6% under the EPAD and LERC scenarios. As a result, the total ES value increased by USD 24.5 and 78.5 million under the EPAD and LERC scenarios for the year 2051, whereas the total ES value was reduced under the BAU and RAE scenarios by USD 27.1 and 73.2 million. The trade-offs among ecosystem services were significantly synergized under the LERC scenario compared to RAE. Therefore, EPAD and LERC could be used as a reference for sustainable landscape planning and management. Landscape ecosystems restoration integrated with a sustainable agricultural intensification approach would enable us to ensure the sustainability of both agricultural production and ecosystem service synergies without negatively affecting the natural environment.

Keywords: landscape; ecosystem services; restoration; scenarios; MLP–ANN; InVEST; trade-offs

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1. Introduction

Landscape ecosystems and the services and benefits that they deliver are under severe pressure due to the cumulative effects of natural ecosystems' (i.e., natural forest, wetland, grassland) conversion to agriculture and urban areas [1–4]. Demand for staple crops to feed a rapidly growing population is predicted to increase significantly by 2050 [5]. The ever-growing population-related demand for additional tillable land to produce enough food, and the agriculture that is commonly described as smallholder and subsistence, causes the loss and conversion of natural ecosystems [6]. As a result, land degradation, ecosystem fragility, biodiversity losses and ES impairments become the common challenges that affect food security and human well-being [7]. As a result, the estimated cost is approximately USD 4.3 billion per annum due to land degradation in Ethiopia [4]. This indicates that ecosystem conversion-related land degradation is causing important social, ecological and economic problems. Land degradation in the form of soil erosion, soil fertility depletion, excessive surface runoff, deforestation and biodiversity loss is the major environmental hazard that mainly affects the sustainability of agricultural landscapes' productivity [8,9]. The land degradation problem is severe in the Ethiopian highlands (elevation above 1500 m), which accounts for 45% of the total land area the country [2]. Coupled with poverty and climate change, land degradation poses a serious threat to national and household food security.

Similarly, Central Rift Valley (CRV), the study area, is also severely affected by several environmental threats of land degradation (i.e., soil erosion, biodiversity loss, soil fertility reduction, land use change, deforestation, less water productivity, sedimentation, fluctuation in lake water levels) and ES impairments [10–17]. Along with the socio-economic development and fast population growth, the natural ecosystems of the CRV landscape are going through rapid changes [18]. As a result, the habitat quality or biodiversity of the CRV landscape becomes deteriorated and depleted due to LULC changes [19,20], and crop production is reduced by 2–30% [21]. LULC changes causing habitat loss and quality depletion in the CRV landscape mainly correspond to the inappropriate planning, use and management of natural resources (i.e., soil, water, forest) and ecosystems [22]. According to Stefandis [23], the sustainability and productivity of habitats are severely affected by soil erosion. The land degradation problem, due to unintended LULC changes, climate change and biodiversity losses, appears to directly affect the livelihoods and well-being of several million people in the CRV [18,24]. Thus, as pressure on agricultural land increases, there is an urgent need to develop tools to minimize conflicts between competing land uses and increase productivity [22]. Researchers are facing strong expectations regarding their role as key players in producing references for land use planning and management. Although previous studies have widely investigated land degradation-related problems with recommendations that emphasize the importance of land management for the entire CRV landscape, the results are inconclusive and do not offer alternative, spatially explicit land use and management options that aim to enhance the whole ES bundles without trade-offs. In addition, scholars have indicated that more research is needed to reveal scenarios of LULC change [22,25]. Little information is known about the possible future land use change scenarios, and management options are required for the whole CRV landscape [24]. Thus, this study is intended to disclose the future land use options under different management scenarios, thereby providing information on how ES is affected.

Various approaches and modeling tools have been developed to link and assess the impact of potential LULC on ES at landscape and plot scales. The 'Integrated Valuation of Ecosystem Services and Tradeoffs' (InVEST) [26], 'Artificial Intelligence for Ecosystem Services' (ARIES) [27], Co$ting Nature v.3 [28], 'Multiscale Integrated Models of Ecosystem Services' (MIMES) [29] and 'Social Values for Ecosystem Services' (SolVES) [30] are widely used in contemporary ecosystem studies. Of all ecological tools, InVEST is the most widely known and most used model across the globe, with recognized utility for landscape-scale ES studies [31–33]. InVEST is a user-friendly tool with a scenario generator and other important models to assess the processes linking the impacts of land use change and ES under different management scenarios in data-scarce areas [1,33]. In this study, the InVEST model was used to explore different land use change scenarios and predicted LULC using an MLP–ANN model based on various socio-economic and environmental variables. The aim of this study was to explore and analyze alternative landscape management options and related ES trade-offs and synergies in the study landscape. This study attempted to identify the best landscape management options integrated with sustainable intensification as climate change adaptation strategies that enable the agricultural sector to continue to prosper without compromising ES bundles.

2. Materials and Methods

2.1. Study Area Description

The approximate geographical location of the study landscape lies at 38°15′ E and 39°25′ E longitude and 7°10′ N and 8°30′ N latitude, with 10,074 km^2 surface area coverage (Figure 1). It falls within the Great Rift of Ethiopia, with diverse topographic and climatic conditions. It has semi-arid climatic conditions at the rift floor, while the highlands experience humid and sub-humid conditions. The study landscape's altitude ranges from 1646 m near Lake Zeway to approximately 4171 m in the Chilalo-Galama Mountains at the Arsi-Bale massif. The area has a long, heavy rain season from June to September and a short rain season from March to May. The mean annual rainfall of the area ranges from 600 to 1600 mm. The mean minimum and maximum annual temperatures are 16.9 and 21.4 °C.

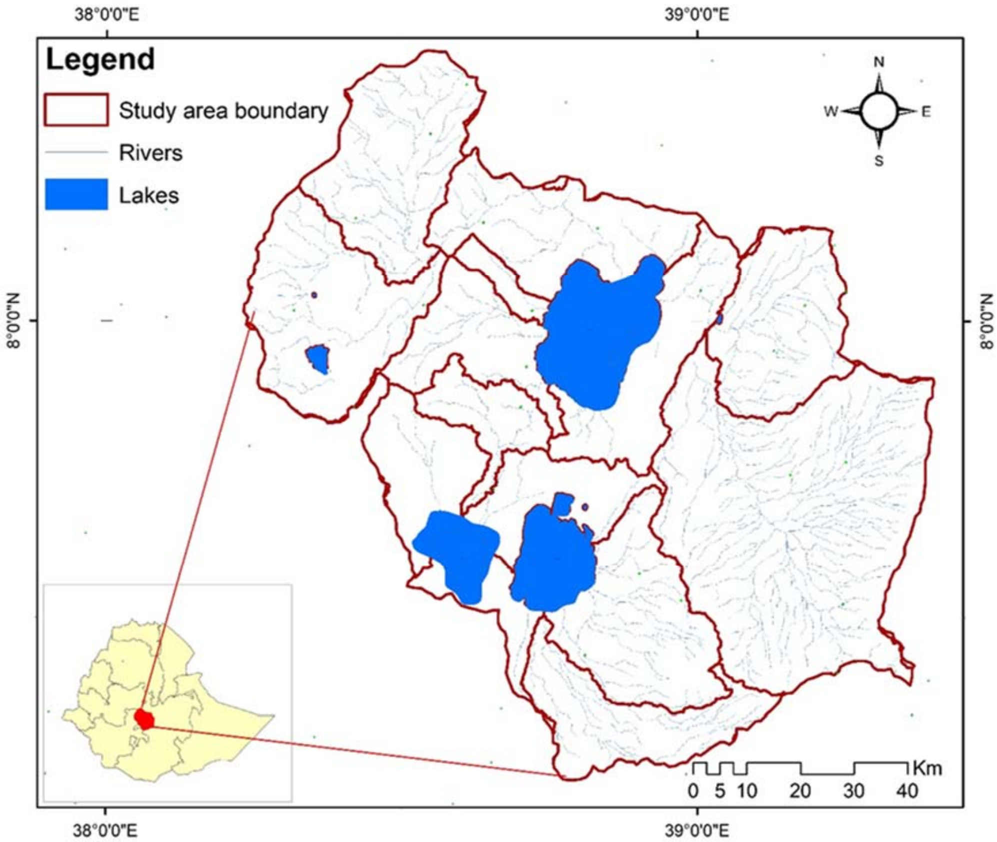


Figure 1. Map of the study area.

Calcaric Fluvisols, Vitric Andosols, Vertisols and Eutric Nitisols are the dominant soil types of the study area. The dominant tree species in the highlands of the study landscape are Eucalyptus camaldulensis, Albezia species, Sesbania sesban, Acacia species, Juniperus procera, Cupressus lustanica, Cordia africana, Olea africana and Croton maycrostachys. The common crops, which include maize (Zea mays), Faba bean (Vicia faba), wheat (Triticum aestivum), tef (Eragrostis tef) and barley (Hordeum vulgare), are produced under rain-fed agriculture.

2.2. Data

In order to simulate LULC scenarios and for habitat quality modeling, different datasets were used from various sources. LULC maps for 2001, 2011, 2021 and 2051 study years were obtained from a previous study by Biratu et al. [24]. Qualitative and quantitative information was extracted from existing spatial land use policies, strategies and plans (e.g., [34–37]); study area population analysis [18]; land suitability analysis; a consultation workshop report on scenarios of agricultural development in Ethiopia [38]; and expert knowledge of the study landscape characteristics.

2.3. Modeling Future LULC Change Scenarios

A total of four future LULC scenarios were simulated in this study, namely Business-as-Usual (BAU), Rapid Agricultural Expansion (RAE) scenario, Ecosystems Protection and Agricultural Development (EPAD) scenario and Landscape Ecosystems Restoration and Conservation (LERC) scenario. These anticipated LULC scenarios were modeled from assumptions that were developed based on qualitative and quantitative information. The assumptions and characteristics of the anticipated four scenarios are described as follows.

Business-as-Usual (BAU) scenario: The assumption in the BAU scenario is that future land use distributions follow historical trends that do not consider new economic and environmental policies. This BAU scenario was simulated based on references of the present day (2001–2021) socio-economic and environmental conditions [24]. Thus, the predicted LULC for the 2051 study year using the MLP–ANN model was used as the BAU scenario in this study.

Rapid Agricultural Development (RAD) scenario: The RAD scenario is characterized by the worst changes and landscape management with no existing environmental policy implementations, and the common subsistence and smallholder agriculture continues to expand. The RAD also posits that population and socio-economic (e.g., irrigation scheme, industries, infrastructure) growth will occur at a higher rate than BAU without a proper plan. This scenario is driven by economic policies towards increasing agricultural production and industrialization in order to secure food and satisfy related demands. Governmental policies are driven by the short-term political aspirations of politicians, rather than effective evidence-based decision making. New cultivated parcel areas would be introduced to other land uses and expand even in the very steep slope lands. In this scenario, attempts are made towards more agricultural production through expanding cultivated land rather than increasing production per unit area.

Ecosystems Protection and Agricultural Development (EPAD) scenario: The EPAD scenario is characterized by integrated land use management that is overwhelmed by protection from further degradation and increasing agricultural production. Policies are implemented to protect natural ecosystems and the government strives to increase production per unit area using agricultural technologies and inputs. Cultivated and bare land are not allowed for further expansion and remain the same as in the baseline year. Forest cover would increase up to 30% every ten years, as per the government plan.

Landscape Ecosystems Restoration and Conservation (LERC) scenario: The LERC scenario is characterized by sustainable ecosystem restoration and sustainable intensification that is dominated by the restoration and conservation of the landscape ecosystems with continued economic growth. Existing environmental policies would be strictly implemented that integrate the protection, conservation and restoration of the ecosystems. In the LERC scenario, the landscape is managed and used based on the suitability of the land. The government and other relevant stakeholders are committed to covering approximately 10% of the landscape with forest, which is based on a land suitability analysis. Forest would replace the cultivated and bare land at very steep slope areas that need to be protected and afforested. Therefore, afforestation of very steep slope and bare land would be implemented in the absence of changes in natural ecosystems (i.e., water bodies, wetland and grazing land). Cultivating very steep land substituted by irrigating high-yield crops together through utilizing the irrigation potential of the study area is effectively implemented to compensate for yield losses due to steep slope cultivation conversions to forest. Sustainable intensification using technologies that increase agricultural productivity (e.g., improved high-yield crop varieties, proper fertilizer and pesticide application, practices and innovations) would be implemented for irrigated and rain-fed agriculture to increase agricultural yields two-to-five-fold, which would contribute towards national food security and fill yield gaps. Family planning to reduce the population pressure is implemented; thereby, population and urbanization growth is restricted and/or retained at a lower rate.

Based on assumptions that described the above simulations, we employed the MLP–ANN and InVEST models. Accordingly, the InVEST model was used to generate the RAD, EPAD and LERC scenarios, whereas the MLP–ANN was used for BAU scenario simulation; details are described in Biratu et al. [24]. In order to simulate the BAU scenario, different variables were considered. Accordingly, slope, elevation, distance from road, distance from market, distance from river, rainfall and population density were used as input variables to simulate the future 2051 LULC using the MLP–ANN model. LULC of 2001, 2011 and 2021 were used for model training and validation in the process of LULC simulation for 2051 for the BAU scenario. The MLP–ANN model validation result was robust, showing 80% correctness, which was checked based on the simulated and observed LULC of 2021 [24].

The InVEST scenario generator proximity-based model was used to simulate the RAE, EPAD and LERC scenarios. An LULC map of 2021 was used as a baseline input in the InVEST scenario generator proximity-based model. Land suitability analysis was performed based on weighted overlay analysis using the ArcGIS model builder, aiming to determine the land demand for restoration. Based on scenario assumptions, important data were used as input for the InVEST model. Accordingly, the maximum area to convert, focal land cover and replacement land cover and number of steps in conversion were determined and used as input for the InVEST model. Thus, LULC codes along the area that needed to be addressed were determined and used for intended scenario simulation. Following land use scenario simulation, LULC area differences (in ha and percent) were calculated and compared to the base year of 2021. The rate of LULC area changes per annum was calculated as follows:

$$ARC(\%) = -\left[1 - \left(\frac{Initial\ year\ LULC\ area}{Final\ year\ LULC\ area}\right)^{\left(\frac{1}{t}\right)}\right] * 100 \quad (1)$$

where ARC (%) is the annual rate of change in percent; t is the time period difference. Accordingly, the initial year was denoted as the base year 2021 and the final year was denoted by each simulated scenario of LULC.

2.4. Estimating ES Values (ESV)

In order to estimate the total ES values, a benefit transfer approach was used, using the modified ES coefficients for the Munessa-Shashemene area in Ethiopia, which is similar to the study landscape. The ES coefficients were modified by Kindu et al. [6] from global ES coefficients developed by Costanza et al. [39] and a valuation database of the Economics of Ecosystems and Biodiversity (TEEB) through a benefit transfer method based on expert knowledge of the study area. The modified coefficients are considered as conservative value coefficients compared to global ES coefficients to estimate the total ES values, and they were used in this study (Table 1).

Table 1. Conservative ES value coefficients (million USD ha^{-1} yr^{-1}) adopted from [6].

LULC	Equivalent Land Cover	ES Coefficient (Million USD ha^{-1} yr^{-1})
Cultivated land	Cropland	225.56
Forest	Tropical forest	986.69
Water	Lakes	8103.5
Grazing land	Grass/range land	293.25
Wetland	Swamps/floodplains	8103.5
Built-up land	Urban	0
Bare land	Desert	0
Shrub-bush land	Grass/range land	293.25

The total ES values were calculated for each LULC scenario using the following steps and equations [6]:

$$ESV_{Kt} = \sum(A_K \times VC_K) \quad (2)$$

where ESV = total estimated ES value, A_k= the area (ha) and VC_k = the value coefficient (USD ha^{-1} $year^{-1}$) for LULC type 'k'.

The total ESV for reference year 't' was calculated by adding the ESV of each LULC class as follows:

$$ESV_t = \sum(ESV_{Kt}) \quad (3)$$

The change in ESV over time was assessed using the following formula:

$$\text{Percent of ESV change} = [(ESV_{t2} - ESV_{t1})/ESV_{t1} \times 100] \quad (4)$$

Thus, the total change in ES value was estimated by calculating the differences between the estimated values for corresponding LULC classes.

Around 16 individual ecosystem functions categorized under provisioning (n = 4), regulating (n = 7), supporting (n = 3) and cultural services (n = 2) in a landscape were calculated by using the following equation:

$$ESV_f = \sum(A_K \times VC_{fK}) \quad (5)$$

where ESV_f = calculated ES value of function 'f', A_k = the area (ha) and VC_{fk} = value coefficient of function 'f' (USD ha^{-1} $year^{-1}$) for LULC type 'k'.

In order to analyze the trade-off and synergies observed between ES, in addition to identifying the relationship between LULC and ES under different scenarios, principal component analysis (PCA) was employed using R software version 4.0.4 which was created by Ross Ihaka and Robert Gentleman at the University of Auckland, New Zealand accessed from (https://cran.r-project.org/src/base/R-4/R-4.0.4.tar.gz, accessed on 30 June 2022).

3. Results

3.1. Land Use and Land Cover (LULC) Changes under Four Different Scenarios

Four simulated scenarios of LULC and their area changes by the year 2051, compared to the base year 2021, in the study landscape are presented in Table 2 and Figure 2. Of all LULC types, cultivated land coverage has the large proportion of 81%, 85%, 66% and 57% under the BAU, RAE, EPAD and LERC scenarios, respectively, in the study landscape (Figure 2). Shrub-bush land and water bodies also have higher area coverage, next to cultivated land, whereas wetland, built-up land and grazing land shared the smallest proportions under all scenarios. Under the LERC scenario, the proportion of cultivated land, forest, water bodies, grazing land, wetland, built-up land, bare land and shrub-bush land accounted for 57%, 12%, 80%, 0.5%, 0.7%, 0.8%, 3% and 18%, respectively. However, the area coverage and pattern of all LULC were varied across all scenarios, with the exception of water bodies.

Table 2. LULC patterns under four different scenarios compared to base year 2021.

LULC	LULC Area in ha					LULC Area Changes in ha (Annual Rate of Change in Percentage)			
	2021	**BAU**	**RAE**	**EPAD**	**LERC**	**2021-BAU**	**2021-RAE**	**2021-EPAD**	**2021-LERC**
Cultivated land	666,489	813,037	860,454	666,489	576,786	146,548 (0.6)	193,965 (0.8)	0	−89,703 (−0.4)
Natural forest	16,677	11,089	5720	48,402	116,757	5588 (−1.2)	−10,957 (−3.2)	31,725 (3.2)	100,080 (6)
Water body	81,584	80,998	80,998	81,584	81,584	−586	−586	0	0
Grazing land	4967	159	71	4035	4967	−4808 (−9.8)	−4896 (−12)	−932 (−0.6)	0
Wetland	6572	5461	533	6572	6572	−1111 (−0.6)	−6039 (−7.3)	0	0
Built-up land	7880	5260	7881	7880	7881	−2620 (−1.2)	1	0	1
Bare land	40,945	43,592	43,595	32,479	30,566	2647 (0.2)	2650 (0.2)	−8466 (−0.7)	−10,379 (−0.9)
Shrub-bush land	182,237	47,755	8099	159,909	182,238	−134,482 (−4)	−174,138 (−9)	−22,328 (−0.4)	1
Sum	1,007,351	1,007,351	1,007,351	1,007,351	1,007,351				

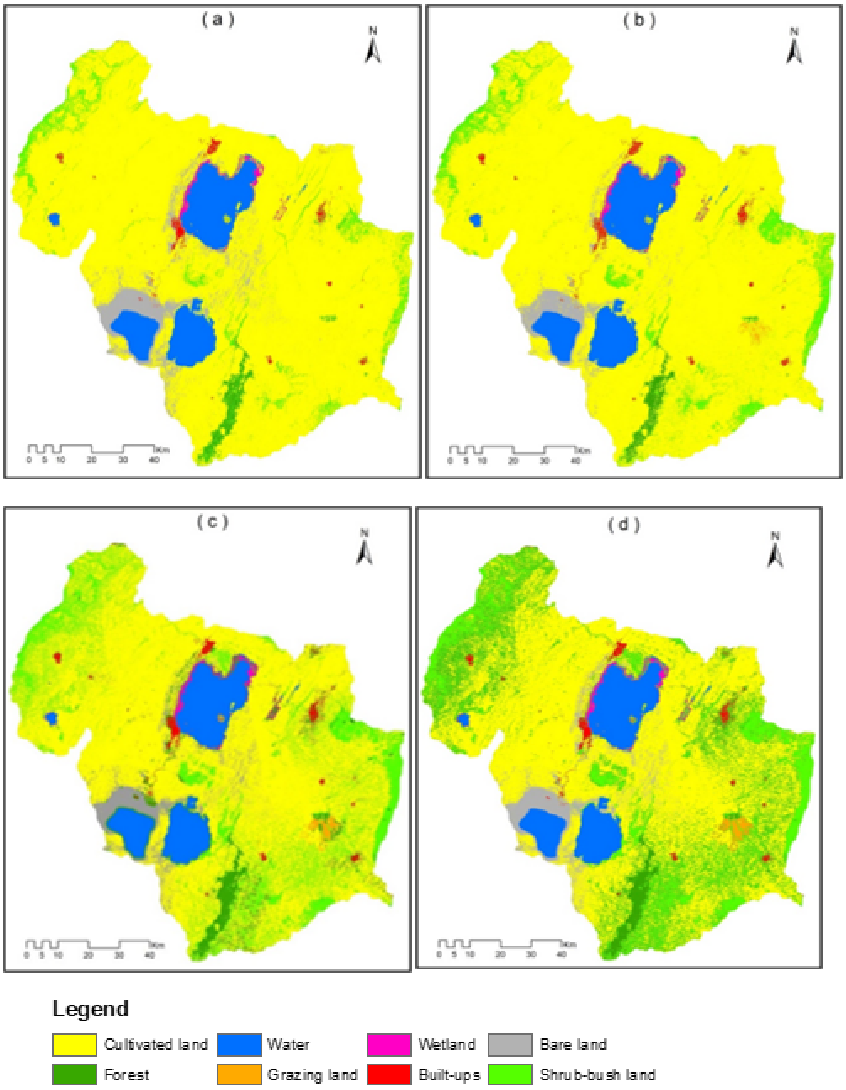


Figure 2. Land use and land cover (LULC) distribution under four scenarios: (**a**) Business-as-Usual (BAU), (**b**) Rapid Agricultural Expansion (RAE), (**c**) Ecosystems Protection and Agricultural Development (EPAD) and (**d**) Landscape Ecosystems Restoration and Conservation (LERC).

Considerable changes in LULC were revealed under the BAU, RAD, EPAD and LERC scenarios compared to the base year 2021 (Table 2). Accordingly, under BAU, forest, water bodies, grazing land, wetland and shrub-bush land decreased, while cultivated land and bare land increased. The extent and trends of cultivated land changes were similar throughout the study landscape. Cultivated land increased by 146,548 ha (22%), mainly at the expense of grazing land, shrub-bush land and wetland. Contrarily, the reduction in grazing land, shrub-bush land, forest and wetland under the BAU scenario accounted for 97%, 74%, 33.5% and 17%, respectively.

LULC changes and patterns under the RAE scenario would continue at a greater rate than in the BAU scenario with a similar trend. The expansion of cultivated land under the RAE scenario also increased by 193,965 ha (29%) compared to the base year 2021. Similarly, bare land increased by 6%. However, grazing land, shrub-bush land, forest and wetland decreased by 99%, 96%, 66% and 92%, respectively, under the RAE scenario. Water area coverage had no significant change. The expansion of cultivated land occurred predominantly for grazing land and shrub-bush land found on steep slopes in the study landscape.

Under the EPAD and LERC scenarios, the change patterns of LULC are different compared to the BAU and RAE scenarios. Slight or no changes were attributed to the LULC in natural ecosystems such as water bodies, wetland and cultivated land under EPAD. Shrub-bush land, grazing land and bare land decreased and were replaced by forest under the EPAD scenario. In the LERC scenario, forest cover significantly increased by 100,080 ha, whereas cultivated and bare land decreased immensely, by 89,703 ha and 10,379 ha. Overall, the annual rate of change analysis shows that forest cover increased at a higher rate under the EPAD and LERC scenarios, whereas grazing land, shrub-bush land, forest and wetland decreased at a higher rate under the BAU and RAE scenarios.

3.2. Ecosystem Service (ES) Value Changes under Four Different Scenarios

We estimated the total ES values and their changes under the BAU, RAE, EPAD and LERC scenarios by the year 2051 compared to the base year 2021, as illustrated in Table 3. The total ESVs under BAU, RAE, EPAD and LERC were estimated at approximately USD 909, 863, 960.5 and 1015 million, respectively. Among the four simulated scenarios of the LULC changes, RAE exhibited the lowest total ES values and LERC was the highest. Similarly, BAU exhibited the second-lowest value compared to the EPAD and LERC scenarios. Accordingly, the total ESVs were reduced by USD 73 and 27 million under the RAE and BAU scenarios compared to the base year 2021. Contrarily, the total ESVs under the EPAD and LERC scenarios increased by USD 24.5 and 79 million compared to the base year 2021. Among all LULC, cultivated land increased the ES value by USD 44 (29%) million, while the remaining LULC decreased the ES values significantly. Similarly, cultivated land is the only LULC type that increased the ES value compared to the other LULC in the study area. However, this was not the case under the LERC and EPAD scenarios, where ES values were reduced by USD 20 million and exhibited zero values due to cultivated land. The highest ES value increased due to forest under the EPAD and LERC scenarios by USD 31.3 and 99 million by the year 2051 compared to the base year 2021. Overall, the total ES values significantly decreased under BAU and RAE compared to the base year 2021. Meanwhile, ES values showed a significant increase under the EPAD and RLEC scenarios compared to the base year 2021.

Table 3. The total ES values (ESV) under different LULC change scenarios in million USD ha^{-1} yr^{-1} (percentage change).

LULC Class	ESV USD Million ha^{-1}yr^{-1}					ESV Changes in USD Million h^{-1} under Three Scenarios Compared to the Base Year 2021 (Percentage Change)			
	2021 Base Year	BAU	RAE	EPAD	LERC	BAU	RAE	EPAD	LERC
Cultivated land	150	183	194.1	150.3	130	33 (22)	44 (29)	0.0	−20 (−140)
Natural forest	16	11	5.6	47.8	115	−6 (−34)	−11 (−66)	31.3 (190)	99 (600)
Water body	661	656	656.4	661.1	661	−5 (−0.7)	−5 (−0.7)	0.0	0
Grazing land	1	0	0.0	1.2	1	−1.4 (−97)	−1 (99)	−0.3 (−19)	0
Wetland area	53	44	4.3	53.3	53	−9 (−17)	−49 (−92)	0.0	0
Built-up land	0	0	0.0	0.0	0	0	0	0.0	0
Bare land	0	0	0.0	0.0	0	0	0	0.0	0
Shrub-bush land	53	14	2.4	46.9	53	−39.4 (−74)	−51 (−96)	−6.5 (−12)	0
TOTAL	936	909	862.8	960.5	1015	−27 (−3)	−73 (−7.8)	24.5 (3)	79 (8)

3.3. Trade-Off and Synergies between ES under Different Scenarios

Approximately 16 individuals of ES were estimated in terms of their values for different simulated scenarios, and the relationships among ES are presented under the categories of provisioning, regulating, supporting and cultural services in Figure 3. The combined values of the total provisioning services (i.e., food production, genetic resources, raw materials and water supply) increased by USD 6.7 and 1.5 million under the BAU and EPAD scenarios. Contrarily, the combined value of the total provisioning services was reduced under RAE and LERC by USD 0.4 and 3.6 million. The combined values of the total regulating services decreased by USD 30.7 and 67.8 million under the BAU and RAE scenarios, whereas they increased by USD 16.5 and 60.8 million under the EPAD and LERC scenarios. Similarly, the combined values of the total supporting services decreased by USD 2.8 and 4.3 million but increased by USD 6.3 and 20.7 million under the EPAD and LERC scenarios. Figure 3 indicates that all individual ES values increased together and had positive relationships under the EPAD and LERC scenarios.

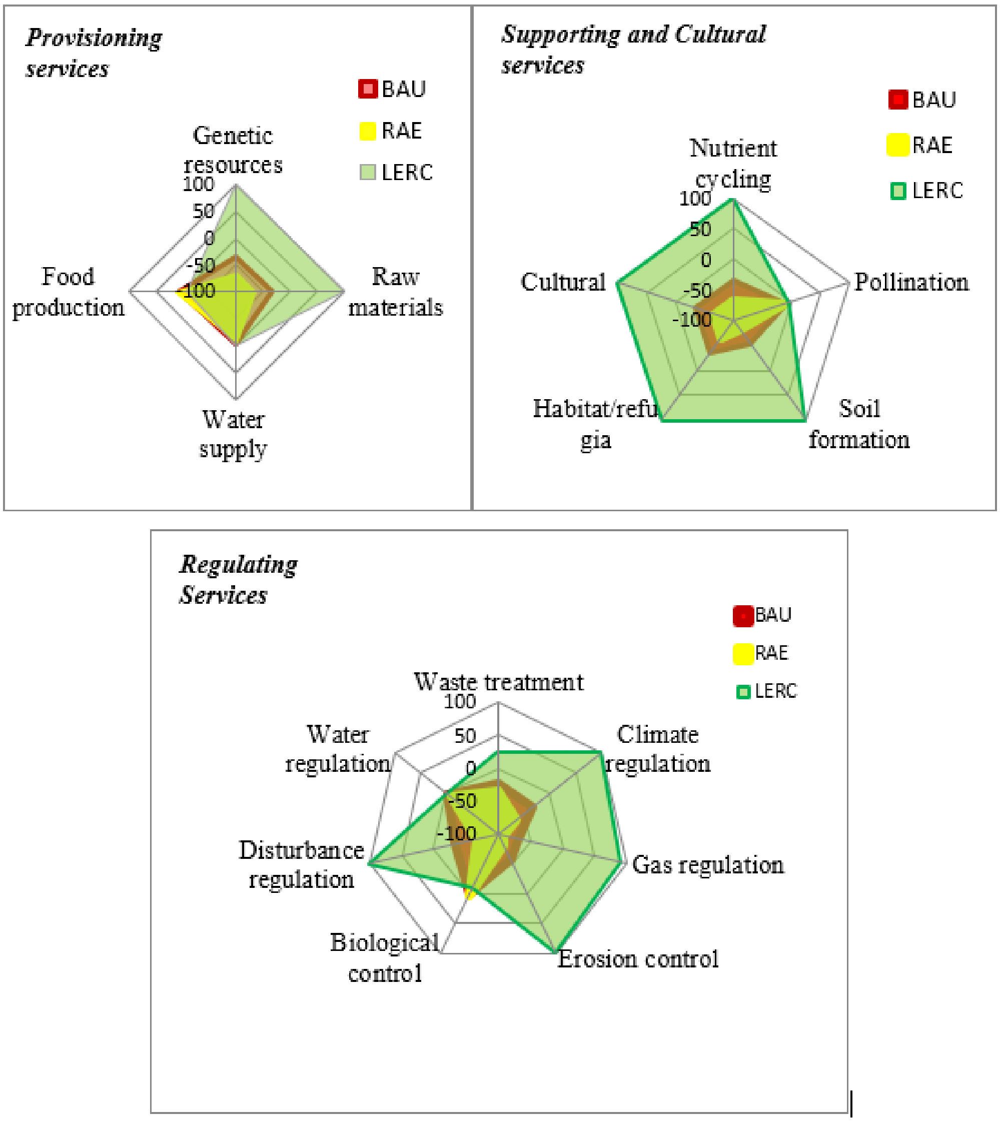
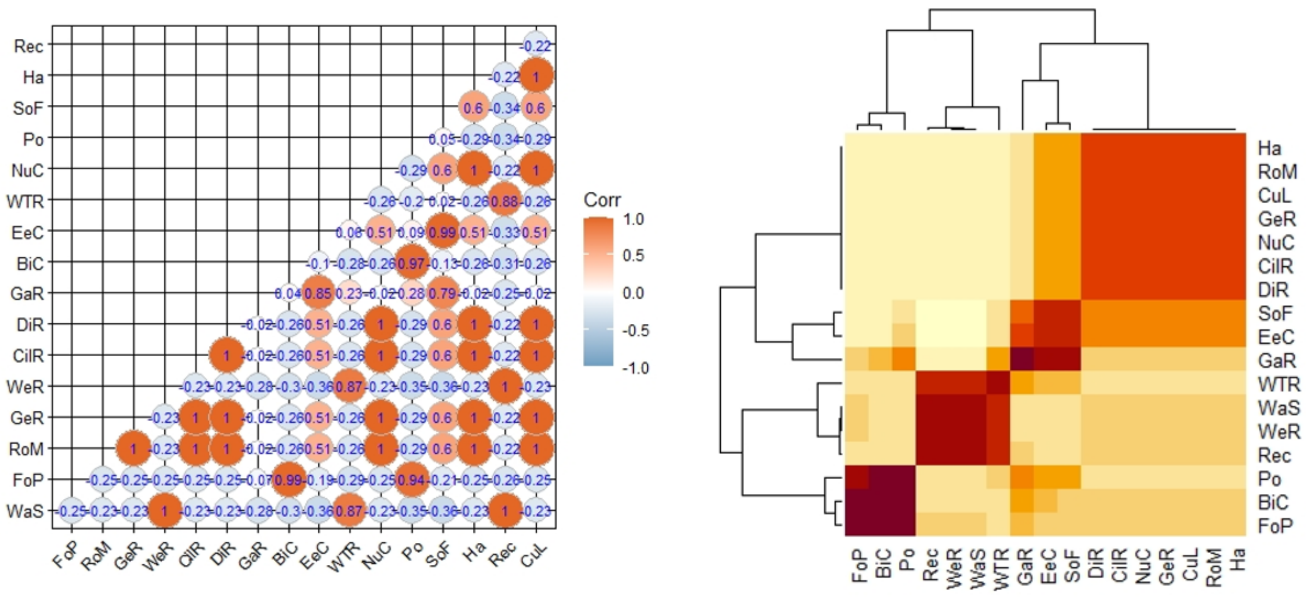
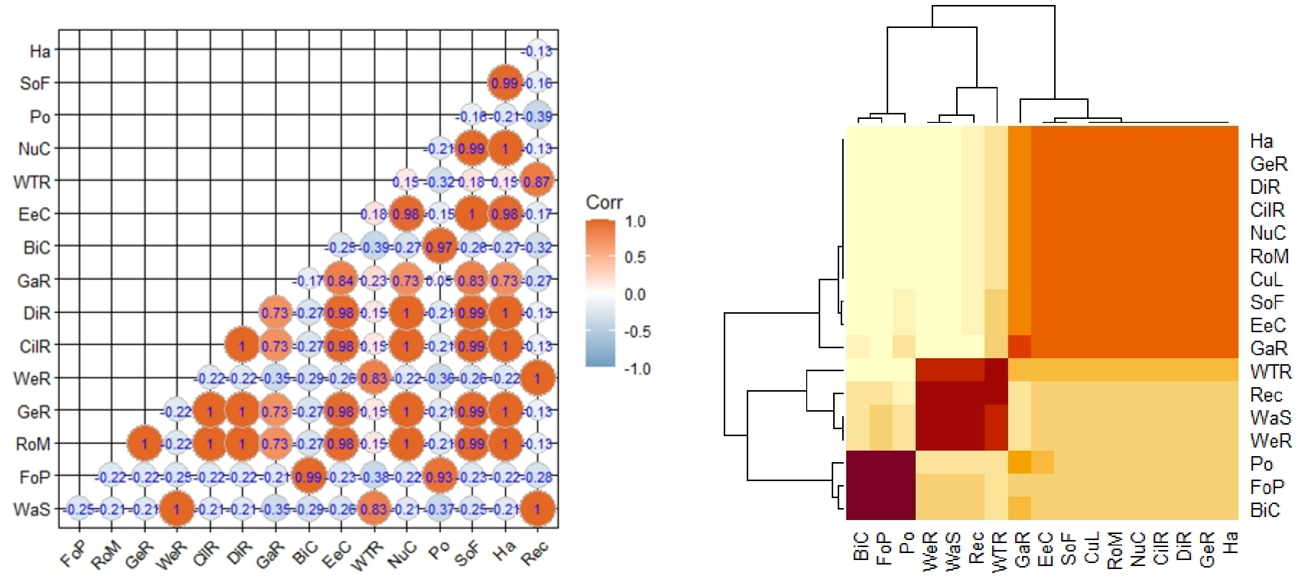


Figure 3. Radar graphs of ES changes in percent compared to the base year 2021 and their associations across four simulated scenarios: Business-as-Usual (BAU), Rapid Agricultural Expansion (RAE) and Landscape Ecosystems Restoration and Conservation (LERC).

In order to assess the trade-offs and synergies between ES, correlation analysis was employed through PCA, and the results are presented in Figure 4. We purposely selected the RAE and LERC scenarios' PCA results to present the trade-offs and synergies between ES. A negative correlation between ES shows trade-offs and a positive correlation shows synergies between ES. The number of ES that have a negative correlation under RAE is high and the number of ES that have positive correlations under LERC is high.



(**a**) Correlations (left side) and heatmap (right side) plots for RAE scenario



(**b**) Correlations (left side) and heatmap (right side) plots for LERC scenario

Figure 4. Correlations and heatmap plots under (**a**) and (**b**) present relationships between ES under RAE and LERC scenarios. Note: (**a**) is an ES (variables) factor map that is labeled with ES; these are selected as shown on the plane; (**b**) is a graph that shows the correlations between ES. Each ES is denoted as follows: water supply (WaS); food production (FoP); raw materials (RoM); genetic resources (GeR); water regulation (WeR); climate regulation (CilR); disturbance regulation (DiR); gas regulation (GaR); biological control (BiC); erosion control (EeC); water treatment (WTR); nutrient cycling; (NuC); pollination (Po); soil formation (SoF); habitat/refuge (Ha); recreation (Rec); cultural (CuL).

As per the number and color differences observed in Figure 4a,b, the trade-offs (negative correlations) between ES are very high under RAE, whereas they are very low under LERC. However, synergies (the number of ES positively correlated) under the LERC scenario were very high. Of all 120 pairs of ES, a substantial number of pairs of ES have shown the highest positive correlation (with corr value, >0.95) and a modest positive correlation (with corr value, 0.1–0.95) under the LERC scenario compared to RAE and the other two scenarios (Figure 4). Accordingly, among 64 positively correlated pairs of ES, 42 of them show a very high, positive correlation under the LERC scenario. Meanwhile, under the RAE scenario, among 35 positively correlated pairs of ES, 27 of them show a very high correlation. Under the LERC scenario, pairs of ES that have a positive correlation and a very high correlation increased by 15 and 29 compared to the RAE scenario. This implies that synergies between ES are significantly improved under LERC. Contrarily, pairs of ES with negative correlations (trade-offs) increased by 29 ES pairs under the RAE scenario compared to LERC. Generally, a negative correlation or trade-off is observed between ES under the RAE scenario compared to LERC. PCA results also show that of all land use types, forest is significantly correlated with raw materials (RoM), genetic resources (GeR), climate regulation (CilR), disturbance regulation (DiR), nutrient cycling (NuC), habitat/refuge (Ha) and cultural (CuL) services under the RAE scenario. Meanwhile, water body has a high value for recreation (Rec), water regulation (WeR), water supply (WaS) and water treatment (WTR) services. Similarly, under the LERC scenario, forest has significant positive correlations with cultural (CuL), habitat/refuge (Ha), disturbance regulation (DiR), raw materials (RoM), nutrient cycling (NuC), climate regulation (CilR), genetic resources (GeR), soil formation (SoF) and erosion control (EeC) services. Meanwhile, water body has high values for water supply (WaS), water regulation (WeR) and recreation (Rec) services. Hence, forest should be the focal land use in order to influence positively most of the ES in the landscape.

4. Discussion

Exploring future LULC change scenarios is paramount for sustainable landscape ecosystem restoration and management decisions. This study revealed the future landscape management trajectories with their implications on ES and biodiversity, which enables us to choose evidence-based management options and support the appropriate decisions. The LULC changes of the study landscape significantly vary across simulated scenarios. The expansion of cultivated land and bare land significantly increased under the BAU and RAE scenarios, while the remaining land uses, such as forest, wetland and grazing land, substantially decreased compared to the baseline. These patterns could be attributed to rapid population growth-related cultivated land demand and expansion for crop production. According to [2,18,40], LULC in Ethiopia has been rising dramatically, as in most countries within sub-Saharan Africa. These changes inter alia are driven by the demand for agricultural land in the face of the rising population and food demand. Ethiopia’s population has more than doubled in the last three decades and is further projected to increase by 2050. These patterns could further explain the projected scenario under the BUA conditions. Further, the agricultural patterns, as currently practiced, will not change if the current limited investments in resource-poor farmers continue [18]; this could further undermine any expected environmental regeneration scenario situations. Meanwhile, the highest changes in the RAD scenario are due to poor adaptation to climate change and the deteriorating effectiveness of governance, with rapid policy shifts based on poor or absent evidence. They are also due to the ongoing influences of factors that continue the previous trends and aggravate the changes across the landscape. Converting natural ecosystems and tilling land, including afro-alpine vegetation on very steep slopes for the production of annual cereal crops, were the major reasons for the observed patterns. In addition, the study landscape is one of the central areas for most of the socio-economic development activities (e.g., industries, irrigation schemes, mining, factories and infrastructures) in the country, with rapid population growth and pressure being responsible for the unintended abrupt changes. As a result, habitat areas with high ecological importance have been severely affected and fragmented in the landscape. These problems are commonly related to policies that favor only agricultural production [18,22,24]. In this study, water area showed the least change compared to the other land uses under all scenarios. These slight changes in water area were also reported in a previous study on the past forty years in the study landscape [24]. Therefore, these severe problems observed in the landscape would similarly continue or become aggravated, to affect the ES and human well-being in the future under the BAU and RAE scenarios. By the year 2051, the total ES values will be reduced by USD 27 and 73 million under the BAU and RAE scenarios compared to the base year 2021. This is due to LULC conversion-related landscape degradation in the landscape. It is in line with several studies on ecosystem service valuation in different parts of Ethiopia [3,6,7,41–46]. Trade-offs were also observed between provisioning services of food production and 14 other ES, except biological control; see Figure 3. Accordingly, the RAD scenario highlighted the trade-offs (negative correlation) between 85 pairs of ES out of the total 120 ES pairs. This implies that trade-offs could occur significantly across space and time under the RAD scenario compared to LERC and EPAD. In this case, most ES would be lost or reduced in importance, while few ES appear. This is due to substantial projected increments in cultivated and bare land, while others will be reduced. Moreover, large amounts of deforestation and conversion of natural ecosystems exhibited in the area would be continued, affecting ES bundles at a higher rate under RAD and BAU. The results indicate strong trade-offs between provisioning ES and each regulating, supporting and cultural service regardless of the sustainable intensification component expected to be implemented under the EPAD and LERC scenarios. We thus reveal that LERC and EPAD are the ideal options to restore and preserve the landscape ecosystems compared to BAU and RAE. This is because these scenarios will provide strict implementation of existing environmental policies for natural ecosystems' (i.e., forest, wetland, lakes) protection and restoration. Strict implementation of existing spatial policies includes the designation, demarcation, protection, conservation and restoration of forests, as well as the protection of banks of water bodies through afforestation and the control of the harmful effects of water [34,35]. Accordingly, forest development will need to be a focal issue; forests are mostly categorized as protected and/or productive forests, as per the Ethiopian Forest Development, Conservation and Utilization Proclamation. Accordingly, protected forests shall be forests designated to be conserved and developed free from human or with minimal interference for the purpose of watershed management and the conservation of genetic resources, biodiversity and the environment in general, as well as for the purpose of training and research. Meanwhile, productive forests shall be designated for the production of industrial, construction and other forest products. Under the LERC scenario, productive forests are one type of forest development that can help to establish production industries (i.e., factories producing products such as paper, timber, furniture, raw materials, construction and furniture), thereby it will increase job opportunities for young people and bring substitution economic benefits for wood-related products regardless of environment protection [40,47]. This implies that under the LERC scenario, forest development could incorporate both productive and protected forests in areas with very steep slopes and highly degraded, which are not suitable for crop production, to enable sustainable landscape transformation. Economic benefits from tourism and payments for ecosystem services provided through REDD+ projects could also be an additional source of income under the LERC scenario [22]. Furthermore, sustainable intensification will need to be implemented under the LERC scenario using agricultural technologies, climate-smart practices and irrigation agriculture. Therefore, proper implementation of sustainable intensification could increase staple crop yields by 20–250% per annum, regardless of anticipated irrigation in the landscape [9,21,48]. Under the LERC scenario's anticipated sustainable intensification via agricultural technologies and year-round food production through large-scale irrigation potential, which is estimated as 47,700 ha in the study landscape [49], we could reverse the observed trade-offs between food production and other ES. The whole ES delivery can be enhanced under the LERC scenario without adversely affecting the agricultural production in the studied landscape. In order to realize the LERC scenario, the government must establish a stable institution and policy environment with evidence-based polices that take a long-term perspective, and with a strong ability to adapt, where agricultural investments lead to increasing prosperity and clear recognition and management of trade-offs' levels of climate change impact [18,22,38]. LERC scenarios can be used as a reference for policymakers for future sustainable landscape ecosystem restoration and resource conservation. Further studies that combine rigorous small-scale field experiments with broad-scale assessment would be paramount to identify site-specific technologies that enhance sustainable intensification and to explore the spatial patterns of individual ES under different scenarios. It is also important to assess the acceptability of the LERC pathway as a form of innovative land use.

5. Conclusions

This study used LULC projected under the BAU scenario using a Multi-Layer Perceptron–Artificial Neuron Network (MLP-ANN) model and simulated LULC patterns under the RAE, EPAD and LERC scenarios using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model in order to estimate ES values and analyze ES trade-offs. The result revealed that under the BAU and RAE scenarios, ecosystems would be under severe pressure due to the expansion of agriculture and degraded areas, while the remaining forest, wetland, grazing land, water bodies and shrub-bush land continue to decrease. Contrarily, under the EPAD scenario, there are slight or no changes in cultivated land, water bodies and wetland, while shrub-bush land, grazing land and bare land are converted to forest and show a reduction trend. Under the LERC scenario, forest cover has significantly increased, whereas very steep cultivated land and bare land are converted to forest. Besides continuing forest development, the LERC scenario is assumed to promote sustainable intensification that entails agricultural technologies and year-round cultivation via irrigation, aiming to substitute crop yields from steep land cultivation and reduce yield gaps. The LERC scenario also promotes quality governance, stable institutions and a policy environment that holds a long-term perspective. As a result, the total ES values are reduced by USD 73 and 27 million under the RAE and BAU scenarios com-pared to the base year 2021. Contrarily, the total ES values under the EPAD and LERC scenarios are increased by USD 24.5 and 79 million compared to the base year 2021.Trade-offs among ES could be managed by 24.2% and synergy of ES enhanced by 35.7–47% under the LERC scenario compared to RAE. Therefore, under the EPAD and LERC scenarios, the landscape would be able to meet the agricultural production demand by 2051 without the need to expand cultivated land. The LERC scenario could be used as a reference for sustainable landscape planning and management of the studied and similar landscapes. Landscape ecosystem restoration could be integrated with a sustainable agricultural intensification approach, enabling us to ensure the sustainability of both agricultural production and ecosystem service synergies without negatively affecting the natural environment, thus permitting us to achieve the Sustainable Development Goals (i.e., SDG 2; SDG 10; SDG 15).

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