Rapid assessment of potential changes in habitat quality, carbon and soil retention services: Comparison of scenarios

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1   INTRODUCTION AND RATIONALE

Over the past two decades, Rwanda has established itself as one of the fastest growing economies in Africa and the world as a whole (World Bank, 2020). Under the recently-formulated Vision 2050, the country has set ambitious goals of achieving upper middle-income status by 2035 and high-income status by 2050 (Republic of Rwanda, 2020). At the same time, Rwanda's land and natural resources are under severe pressure. With a population density of over 500 people/km^2, Rwanda is the most densely-populated country in mainland Africa (World Bank, 2023). This has driven extensive conversion of natural habitats to farmland and settlement, with remaining sizeable blocks of natural habitat now largely limited to a handful of strict protected areas. Competition for land is intense, with the average agricultural household owning just 0.76 ha, a figure which continues to decline as the population expands (REMA, 2021). Rwanda also remains highly dependent on biofuels, which account for 85% of the energy mix (REMA, 2021) These and other threats result in very high encroachment and conversion pressures on natural ecosystems.

While the expansion of farming and settlement have been necessary to keep pace with the needs of Rwanda's population, they have resulted in costs such as increased soil erosion and sedimentation rates, elevated landslide and flood risks, scarcity of wood and other natural resources and the loss of biodiversity. In response, the Rwandan government has enacted policies and legislation governing land use and environmental protection over the past two decades, with a particular emphasis on erosion control to promote more sustainable agriculture (Bagstad *et al.*, 2020). Efforts have also been made to reduce deforestation and restore forest cover. Although this has involved the restoration and improved protection of natural forest in some cases, it has more typically involved the planting of fast-growing exotic species (Republic of Rwanda, 2019) which do not add ecological or biodiversity value. Rwanda has also been one of the pioneering African countries in developing natural capital accounts, including ecosystem accounts (NISR, 2019). This reflects the country's increasing recognition of the importance of services provided by its ecosystems. Despite these efforts, remaining natural habitats continue to experience significant risks of encroachment and degradation, including in protected areas such as Nyungwe National Park (Republic of Rwanda, 2016). Additionally, demand for woodfuel currently exceeds supply, adding to the pressure on woody ecosystems (REMA, 2021). Hence, despite efforts to improve the protection of biodiversity in the country, the current trajectory still threatens to further undermine Rwanda's natural resource base.

This study contributes to the update of Rwanda's 2020 Future Drivers of Growth (FDG) report (World Bank, 2020), which outlines a vision for the country's development policies. The updated report addresses gaps relating to climate change and the environment which received limited attention in the previous version, specifically identifying ways to reduce Rwanda's vulnerability to climate change while curtailing the degradation of natural capital which is critical for the supply of ecosystem services. The study considers potential changes in carbon storage, soil retention and habitat quality (or biodiversity) under a two future land use scenarios, namely a Business as Usual (BAU) scenario and an Aspirational Scenario. Under the BAU scenario, it is assumed that no significant changes would be made to enhance the protection and health of natural capital in Rwanda. In contrast, the Aspirational Scenario represents an ambitious plan to restore natural capital, while still accounting for intense and increasing future pressures like agriculture and urbanisation. Projected land cover layers were created for these two scenarios, and the differences in the delivery of the three ecosystem services were evaluated.

2 SCENARIOS

The two scenarios considered in the study are: (i) Business-as-Usual (BAU) which represents future patterns of activity assuming that there will be no significant change in priorities or policy and baseline circumstances continue unchanged, and (ii) an Aspirational Scenario which assumes that cropland and settlement expansion pressures would continue, but increased efforts would be made to rehabilitate and improve the protection of natural habitats relative to BAU, in combination with better planned and more spatially efficient urbanisation.

2.1 BUSINESS-AS-USUAL SCENARIO

Under a BAU Scenario, it is assumed that there are no changes in policy or interventions to address the existing threats to habitats and biodiversity. It was thus based on the analysis of past land cover trends in Rwanda, assuming that these trends would continue on into the future at similar rates. Rwanda is already dominated by agriculture, with only a few remaining "islands" of sizeable natural habitat left within protected areas. Between 1960 and 2007, for example, it is estimated that natural forests declined in extent by 65%, with further losses having occurred since (Republic of Rwanda, 2016) . The main threats to forests and other natural habitat include the country's dense and growing human population, which drives further conversion of habitats to settlement, crops and grazing land, as well as increasing the demand for fuelwood and other natural resources. Encroachment pressures around remaining natural habitat blocks in protected areas are severe, many of which have hard edges between natural vegetation inside the park and the dense "sea" of cultivation outside the boundary (Republic of Rwanda, 2016).

2.2 ASPIRATIONAL SCENARIO

The Aspirational Scenario represents an ambitious plan to improve the health of natural capital in Rwanda relative to BAU, while still accounting for intense and increasing future pressures like agriculture and urbanisation. It was guided by a range of planned and proposed land management interventions that have been put forward by a range of Rwandan agencies, with a focus on interventions associated with biodiversity goals and benefits. Additionally, an effort was made to limit the proposed interventions to what might be realistically feasible in light of economic constraints and the intense competition for land in Rwanda.

Data sources used to inform the identification and mapping of interventions included the potential protected area expansion and wildlife corridor options identified in Rwanda's National Biodiversity Strategy and Action Plan (NBSAP) (Republic of Rwanda, 2016) and plans for future forest and wetland gazettement mapped by the Rwanda Forest Authority (RFA) and the National Environmental Management Agency (NEMA). The study also included some of the restoration actions identified in the Catchment Restoration Opportunities Mapping (CROM) for Rwanda report (ESRI Rwanda, 2018). Information on urban densification was extracted from the Rwanda Country Climate and Development Report (CCDR) (World Bank, 2022) and available information on the ongoing Rwanda Urban Development Project II.

3   DATA AND METHODS

3.1   OVERVIEW

The changes in land cover by 2050 under the BAU and Aspirational Scenarios were assessed on the basis of past land cover data trends, and potential interventions proposed for Rwanda under an Aspirational Scenario. The assessment focused on changes in the delivery of three ecosystem services under these two future scenarios, namely global climate regulation, soil erosion and sedimentation control and habitat quality. The data and assumptions used for modelling each of these services is described in detail below. The assessment is designed to provide an indication of the potential direction, magnitude and spatial pattern of trends, and the limitations of the data and models need to be kept in mind.

3.2   PREPARATION OF LAND COVER LAYERS FOR THE BAU AND ASPIRATIONAL SCENARIOS

3.2.1   ASSESSMENT OF HISTORICAL LAND COVER TRENDS

The estimation of future landcover under a BAU Scenario required an analysis of past trends. To assess historical land cover trends in Rwanda, SERVIR land cover data was selected as it provides a consistent land cover time series over four-time steps (1990, 2000, 2010 and 2015). Additionally, it has a relatively high spatial resolution (30x30 m cell size) and a fairly detailed 14-class classification under the Scheme II grouping. This choice also aligns with Rwanda's early ecosystem accounts work, which used the same land cover data (Bagstad *et al.*, 2020).

For the purposes of modelling habitat quality in particular, additional detail was added to the SERVIR land cover data through reference to the Potential Natural Vegetation Map (PNV) of East Africa (van Breugel *et al.*, 2015) and Rwanda's Forest Cover Mapping Report, which maps forest cover in the country across different natural and exotic forest classes (Republic of Rwanda, 2019). The PNV map provides a depiction of the original distribution of different vegetation types in Rwanda in the absence of human modification. The degradation of forest to shrubland and grassland from fire and other threats is an issue in Rwanda, including in protected areas such as Nyungwe National Park (Republic of Rwanda, 2016). To reflect this, areas currently classed as grassland and shrubland by the land cover within forest vegetation types (as per the PNV map) were considered to represent degraded forest rather than pristine grassland or shrubland. In addition, the majority of remaining forest cover in Rwanda outside protected areas consists of woodlots and plantations of exotic species, with limited biodiversity value relative to indigenous or natural forest. This is evident from the Rwanda Forest Cover Report (Republic of Rwanda, 2019). Although the raw data underlying the Forest Cover Report were not available, the few remaining locations of natural forest outside of protected areas could be approximated.

Land cover changes across the full SERVIR time series were assessed through analysing changes in the overall area of different land cover classes and the production of land cover change matrices, to investigate what the main historical land cover transitions have been. The main changes observed included the expansion of agriculture and settlement into natural habitats and net conversion of forest to shrubland and grassland. These land cover transitions were extrapolated to 2050 using best-fit relationships to match the historical trends.

3.2.2 CREATION OF BAU LAND COVER LAYER

The projected land cover changes were applied to the 2015 land cover layer (the most recent in the SERVIR time series) and modelled using the InVEST Scenario Generator model. While significant land cover change has occurred outside protected areas in Rwanda, land cover inside protected areas has remained fairly stable in recent decades. It was assumed this would continue into the future, and the projected land cover changes were thus limited to the portion of the country outside of protected areas. This was achieved by excluding protected areas from the model. Current land cover inside protected areas was then overlayed back on to the layer of projected land cover outside protected areas generated by the model.

The InVEST Scenario Generator model only allows for one land cover class to be expanded at a time, requiring the various transitions to be modelled in a stepwise manner, with each intermediate layer becoming the input for the next modelling step. This also requires a logical order to be used for the modelling sequence. The first step used was the expansion of settlements into all other habitats, except for waterbodies. This was the most logical starting point, since settlements expand into both natural and agricultural habitats. Once settlements had been expanded by the projected amount, perennial cropland was expanded, followed by annual cropland. Both were allowed to expand into natural habitats, while waterbodies and settlements were excluded, since these are both highly unlikely transitions. The last two steps were the conversion of forest to grassland and shrubland. By the final step, a BAU land cover for 2050 had been generated, which incorporated all the major land cover change projections derived from the historical land cover analysis.

3.2.3 CREATION OF ASPIRATIONAL LAND COVER LAYER

For the Aspirational Scenario, various planned and proposed interventions to improve land management were mapped, with a focus on interventions that would increase biodiversity value. At the same time, it was acknowledged that the expansion of cropland and settlement is unlikely to be totally avoided, but that the various interventions proposed under this scenario would ultimately contribute to a smaller agricultural and urban footprint relative to BAU. The projected expansion of cropland and settlement as per the BAU land cover was thus used as the initial starting point, which provides an indication of the likely trajectory in the absence of major policy changes and efforts to improve biodiversity health and protection. Various proposed interventions to improve the status of biodiversity health under the Aspirational Scenario were then mapped, and changes made to the BAU land cover were made accordingly.

The interventions included in the Aspirational Scenario and the adjustments made to the BAU land cover are summarised in Table 1. In addition to these land cover adjustments, the map of current protected layers was adjusted to include all the proposed protected area expansion areas.

Table 1. Summary of interventions under the Aspirational Scenario and changes made to the BAU land cover to reflect these.

Intervention	Changes made to BAU land cover
Proposed expansion areas for Volcanoes National Park and forest reserves identified for future gazettement by RFA.	Any cropland, grassland and shrubland converted to medium forest.
Potential forest corridors (1 km wide) to improve connectivity of PAs in western Rwanda, approximated from maps in the NBSAP.	Any cropland, grassland and shrubland converted to medium forest.
Other proposed protected areas from the NBSAP within forest vegetation types (as per the PNV map).	Any cropland, grassland and shrubland converted to medium forest.

Intervention	Changes made to BAU land cover
New reserves proposed for gazettement by RFA and the NBSAP falling in bushland and savanna vegetation (as per PNV).	Any cropland and grassland converted to shrubland.
Wetlands identified for strict protection.	Any cropland within the protected zone converted to wetland.
Degraded forest areas identified for reforestation by the CROM DSS (assumed indigenous species).	Any cropland, grassland and shrubland converted to medium forest.
Degraded shrubland and savanna areas identified for restoration by the CROM DSS.	Any cropland converted to open shrubland, open grassland converted to closed grassland, open shrubland converted to closed shrubland.
Creation of 10 m riparian buffers along all streams and rivers.	Cropland and grassland adjacent to streams converted to new woody vegetation buffers land cover class, taking into account that only 1/3 of each 30x30 m pixel would consist of buffer vegetation.
Areas identified for afforestation and bamboo planting by CROM DSS (assumed not all indigenous).	Cropland and grassland converted to semi-natural medium forest.
Areas identified for agroforestry by CROM DSS.	Annual and perennial cropland converted to new annual/perennial cropland with agroforestry land cover classes.
Denser, more efficient urbanisation concentrated around Kigali and the six secondary cities prioritised in the Rwanda Urban Development Project II.	Densification and some expansion of urban areas around Kigali and the six secondary cities, all projected urban expansion elsewhere in the country was reversed.

3.3   MODELLING OF ECOSYSTEM SERVICES

3.3.1   CARBON RETENTION

The storage of carbon by vegetation (as above and belowground biomass) and soil (as soil organic carbon) was used as the measure of the carbon retention service. For mapping aboveground biomass (AGB), the recently produced national map of aboveground carbon for Rwanda was selected (Mugabowindekwe et al., 2023). This dataset used high-resolution aerial imagery and machine learning, in combination with field-based measurements, to map and estimate biomass to the level of individual trees. Field comparisons showed that this local layer gives a much more realistic estimate of carbon biomass in Rwanda's savanna and farmland areas, which is significantly over-estimated in some global biomass datasets (Mugabowindekwe et al., 2023). However, the aerial imagery used by Mugabowindekwe et al. (2023) does not adequately capture the contribution of understorey trees, particularly in dense forest. Hence, it conversely under-estimates biomass in denser forest vegetation. As a result, the biomass estimated derived from this dataset are likely to be conservative. It was still chosen in preference to the global datasets, as the magnitude to which some of these layers over-estimate biomass in farmland is much greater than the extent to which the dataset generated by Mugabowindekwe et al. (2023) underestimates dense forest biomass.

In the absence of a similarly detailed map of BGB, this was instead estimated from the AGB layer using root-shoot ratios for different land cover types from the literature (Jones & Muthuri, 1997; IPCC, 2006, 2019). No fine-scale local map of soil organic carbon (SOC) was found for Rwanda. In the absence of suitable local datasets, the 1x1 km resolution Global Soil Organic Carbon (GSOC) map (FAO and ITPS, 2018) was used. It should be noted that since this layer is less fine-grained than the biomass data and comes from a global dataset, its accuracy is likely to be more limited.

To estimate how carbon storage would change under future land cover, the average current storage of carbon in vegetation biomass and soil across different land cover types was first estimated. To add

further spatial detail to these estimates, this was calculated separately for each province to better account for spatial variability in carbon stocks within each land cover type. Carbon stocks under the BAU and Aspirational Scenarios could then be mapped based on the projected area of each land cover type in a given province, and the average carbon storage for the respective land cover type/province combination. Under the Aspirational Scenario, it was assumed that areas afforested with bamboo and other exotic species would have equivalent biomass to medium forest in the current land cover. The same assumption was made for riparian buffers, though adjusted to reflect the fact that only a 10x10 m buffer width is used in Rwanda.[1] For areas under agroforestry, it was assumed biomass would be intermediate between cropland and sparse forest.

3.3.2   SOIL EROSION AND SEDIMENT CONTROL

The soil erosion and sediment control service was modelled using the InVEST Sediment Delivery Ratio (SDR) model, which was also used to model this service for Rwanda's initial ecosystem accounting work (Bagstad et al., 2020). The model first estimates potential annual soil loss from each pixel using the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978). Potential soil loss from each pixel is then multiplied by the SDR, which has a value between 0 and 1. The SDR estimates the proportion of eroded soil from each pixel which ends up reaching a watercourse, after accounting for downslope deposition. The SDR is also calculated on a per pixel level and varies as a function of the intervening topography and land cover between a given pixel and the nearest watercourse.

The SDR model requires information on topography, rainfall erosivity, soil erodibility and land cover. To match the resolution of the land cover data, the 30 m Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) was used. Rainfall erosivity was mapped using the global layer produced by Panagos et al. (2017). Soil erodibility was estimated from soil property data (sand, silt, clay and organic matter content) obtained from the Africa Soil Information Service (AfSIS) (Hengl et al., 2015). Erodibility was calculated from these layers using the equation provided by (Renard et al., 1997). Finally, the model requires cover management (C-factor) and support practice (P-factor) factors to be assigned to each land cover type. The C-factor accounts for the reduction in erosion resulting from the presence of vegetation cover. These estimates were initially derived from the parameters used by Bagstad et al., (2020), with some modifications based on other literature sources and refinement of the initial results (Wischmeier & Smith, 1978; Clay & Lewis, 1990; Panagos et al., 2015; Fenta et al., 2020). Notably, the P-factor for cropland in Bagstad et al., (2020) was based on a fairly detailed assessment of the status of erosion control measures in Rwanda, thus capturing the current state of supporting practices in the country.

Erosion and sediment export were modelled for the BAU and Aspirational Scenarios, based on the changes in projected land cover and management practices. As with the carbon retention service, the fact that riparian buffers would only cover a third of each 30x30 m pixel was considered in setting parameters for these areas.

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[1] Riparian buffer biomass was estimated using a weighted mean, given that all modelling was conducted at 30x30 m resolution but riparian buffers are just 10 m wide in Rwanda. Hence, in farmland areas it was assumed that a third of the pixel would consist of riparian buffer vegetation (10 x 30 m), while the remainder would consist if cropland (20 x 30 m), with the carbon biomass estimated accordingly estimated from the area weighted mean of medium forest and cropland carbon biomass.

3.3.3 HABITAT QUALITY

The measure of habitat quality and how it would change under the future scenario was derived from the InVEST Habitat Quality model. This model uses habitat quality as a proxy for biodiversity, with habitat quality a function of four factors, namely: each threat's relative impact, the relative sensitivity of each habitat to the different threats, the distance between habitat pixels and threat sources and the degree to which land is under legal protection (Sharp *et al.*, 2020). The focus was on the condition of natural habitats as opposed to croplands, settlements and other transformed land cover types.

Five spatial layers were created as inputs for the calculation of an index of habitat degradation and threat level, namely:

- settlements;
- cropland;
- major roads;
- minor roads; and
- protection status (access).

The first four layers represent sources of degradation, including sources of demand and access routes resource harvesting and grazing. For example, settlements are associated with significant demand for resources, such as woody biomass for fuel, with impacts extending some distance into surrounding rural areas in the case of large urban areas. Cropland was also assumed to degrade habitats surrounding fields, since wood and other resources are likely to be harvested adjacent to fields. Additionally, natural land cover types surrounding cropland land cover pixels often will have experienced some degree of agricultural transformation as fields expand. Roads were selected as another threat layer as they increase human access to natural habitats, increasing levels of resource harvesting and conversion of habitat to cropland. The sixth layer relating to protection levels is used to limit these threats where restrictions on habitat harvesting and conversion are in place. The final layer mapping protection status is used to reduce the severity of these threats where land is under legal protection with restrictions on harvesting and habitat conversion.

The five threat layers were coded into binary presence/absence (1/0) raster layers. The settlement and cropland threat layers were extracted directly from the land cover layer for each scenario. Roads were extracted from Open Street Map data and split into major and minor roads using the 'highway' attribute of the shapefile. All roads classed as trunk, primary or secondary or were assigned to the major category, while remaining road categories were classed as minor roads.

For each threat, the model requires an estimate of how far its impact extends, a relative weighting of the severity of the threat, and how the magnitude of the threat varies with distance (linearly or exponentially). An exponential decay function was assumed to be the best representation of how threat impact varies with distance, as has been found in other studies evaluating the relationship between threats and habitat conversion in East Africa (Damania *et al.*, 2019). Settlements were assumed to have the highest impact radius of 30 km, as they are associated with the densest human populations with associated pressures on surrounding land and natural resources. For these reasons, settlements were also assigned the highest threat weighting. Progressively smaller distance thresholds of 12 km and 8 km were used for minor and major roads, respectively, with threat ratings of 0.8 for major roads and 0.6 for minor roads. The former provide a higher degree of accessibility, hence the assumption of more far-reaching and severe impacts on habitats. Finally, a distance threshold of 6 km was used for cropland, with a threat weighting of 0.8, representing the fact that habitats in close proximity to cropland is likely to experience a fairly high degree of pressure from resource harvesting and livestock grazing. The weighting and distance estimates used for the four threat layers are summarised in Table 2.

Table 2. Relative weighting and maximum distance of impact for the different threats included in the Habitat Quality analysis.

Threat	Threat Weighting	Maximum Distance (km)	Distance Decay Function
Settlements	1	30	Exponential
Major roads	0.8	12	Exponential
Minor roads	0.6	8	Exponential
Cropland	0.8	6	Exponential

To generate the protection status (access) layer, the extent of protected areas was extracted from World Database of Protected Areas (WDPA) data for Rwanda (UNEP-WCMC & IUCN, 2022). Like the threat rasters, this layer is a relative ranking, with a value of 0 representing total protection from disturbance and 1 representing no restrictions on access and use of habitats. For Rwanda, it was assumed that formal protection significantly reduces but does not totally eliminate degradation pressures. For example, Rwanda's National Biodiversity Strategy and Action Plan (NBSAP) notes that national parks still experience pressures from agricultural encroachment, poaching, uncontrolled fires and other threats (Republic of Rwanda, 2016). As a result, an accessibility value of 0.15 was used for protected areas. A value of 1 was assigned to the remainder of the country, representing the general absence of formal legal barriers to access and use of habitats. For the Aspirational Scenario, the protection status layer was adjusted to incorporate planned and proposed protected areas, based on the NBSAP and the spatial layers giving the location of proposed forest areas for gazettement as well as wetlands identified for strict protection.

As noted earlier, additional detail was added to the land cover map for the habitat quality assessment through identifying areas of grassland and shrubland within originally forest vegetation types (as per the PNV map) and using the Rwanda Forest Cover Mapping Report to identify remaining areas of natural as opposed to exotic-dominated forest. Areas of grassland and shrubland within forest vegetation types were considered to be degraded areas and the starting habitat quality reduced accordingly. Similarly, forest cover within protected areas and patches of natural forest approximated from the Forest Cover Mapping Report were assigned a high starting habitat quality, while it was assumed that all remaining forest cover mostly consisted of exotic species. Due to their lower biodiversity value, starting habitat quality was reduced accordingly for the latter areas.

The overall level of habitat quality is calculated by the model and normalised to produce a Habitat Quality Score between 0 and 1, where 1 represents the highest quality habitat (effectively pristine natural condition) in the landscape and 0 represents non-habitat. The model output is a map of the relative habitat quality score applied to all remaining natural habitat.

4   RESULTS

4.1   LAND COVER TRENDS AND PROJECTIONS

4.1.1   HISTORICAL LAND COVER TRENDS

The analysis of SERVIR land cover data reveals a substantial of cropland between 1990 and 2015, mirrored by a large decline in forest cover, as is evident in Figure 1. The combined forest land cover class (dense, medium and sparse forest) was still dominant in 1990, covering 46% of Rwanda's land surface area. By 2015, 60% of 1990 forest cover had been lost, with forest now covering just 18% of the country's land area. Conversely, the area of cropland more than doubled over this period, increasing from 26% of Rwanda's land surface area in 1990 to 56% in 2015.
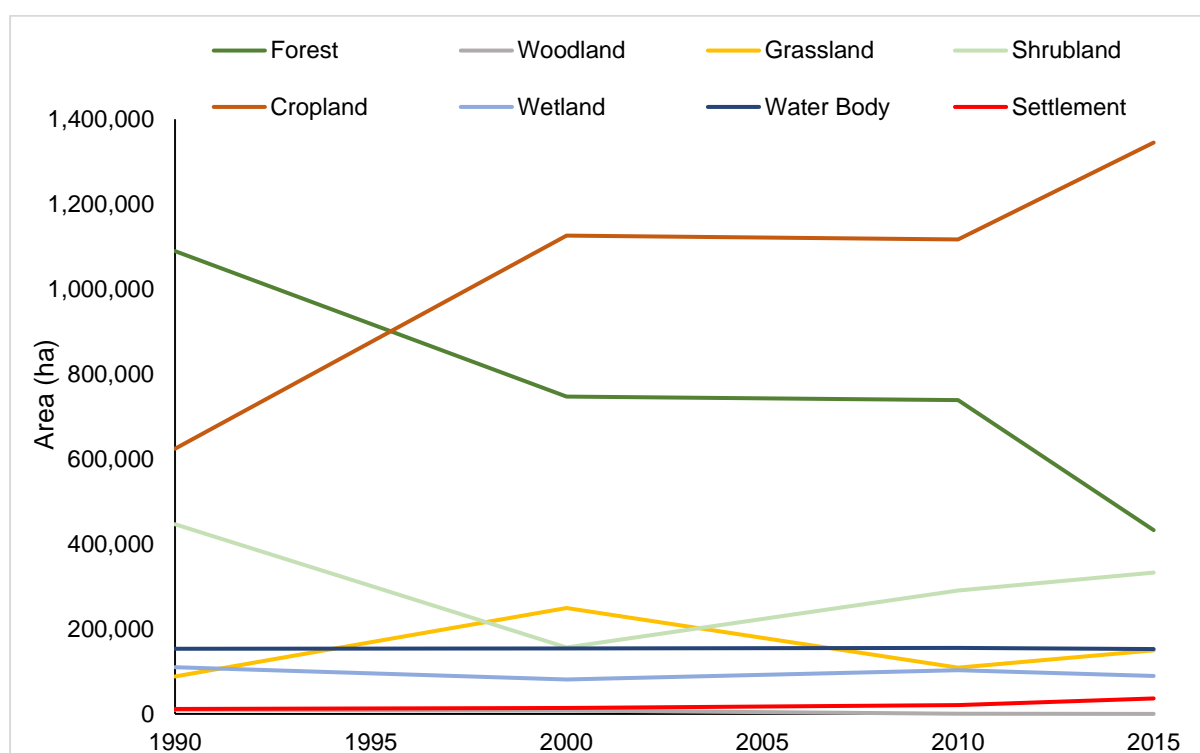

Figure 1. Changes in the area of broad land cover categories between 1990 and 2015, derived from SERVIR land cover data.

Trends in some other land cover classes were more varied, particularly grassland and shrubland which both increased and decreased at various points in the time series. The fact that grassland tended to increase when shrubland decreased (and vice versa) suggests that at least some of this variation is due to inconsistencies in the classification of shrubland and grassland in different years. Overall, the combined area of grassland and shrubland did decline from 1990 to 2015, but not as drastically as forest cover. Settlements expanded rapidly over this period, tripling in area from 1990 to 2015. However, they still accounted for a small portion of total land surface area, increasing from 0.5% in 1990 to 1.5% in 2015. Another notable change was the 19% decline in wetland area, with wetland coverage declining from 4.6% of surface area in 1990 to 3.7% in 2015. Woodland is barely visible in

Figure 1, as it covered just 0.4% of the country in 1990. By 2015, woodland had virtually disappeared from the land cover data, covering less than 1 ha. It is presumed that this is largely due to reclassification of woodland as sparse forest or shrubland.

In addition to assessing overall changes in the extent of different land cover classes, analysis of net transitions between individual land cover classes through a land cover change matrix is helpful for assessing what major transitions have occurred in the past and will likely occur in the future. This indicated that all natural land cover classes experienced a net conversion to cropland (i.e. transitions from natural land cover classes to cropland exceeded transitions in the reverse direction), which would be expected given the significant expansion of cropland that has occurred in the country. Both cropland and natural land cover classes also exhibited a net conversion to settlement, as settlements expand into both farmland and natural areas. A more informative finding was that changes from forest to grassland and shrubland exceeded changes in the reverse direction, indicating a net conversion of forest to grassland and shrubland. Hence, reductions in forest extent over time are due to both the conversion of forest to cropland and settlement, as well as the degradation of forest to grassland and shrubland. This could also explain why the declines in grassland and shrubland over time have not been as drastic as the declines in forest extent, as the conversion of grassland/shrubland to cropland and settlement is partially offset by gains in grassland and shrubland from forest degradation.

4.1.2   LAND COVER PROJECTIONS UNDER THE BAU AND ASPIRATIONAL SCENARIOS

Various best-fit trends were used to project the major land cover transitions to 2050. For annual cropland, a logarithmic curve gave the best-fit to the historical data, as the rate of annual cropland expansion appears to have slowed down in more recent years. Conversely, the extent of perennial cropland increased sharply between 2010 and 2015, with an exponential curve giving the best fit to the data. A linear trend was used to project settlement expansion. Even though an exponential curve also gave a good fit to the data, the projected increase in settlement area by 2050 seemed to be improbably high, hence the use of a linear trend instead. A different approach was used to estimate the amount of forest that would be converted to grassland and shrubland by 2050. Given that the amount of forest remaining in Rwanda declined dramatically between 1990 and 2015, simply extrapolating the area of forest converted to grassland and shrubland over this period could over-estimate the change, as there is a much smaller area of forest to convert by 2015. Instead, it was calculated that net change of forest to grassland and shrubland between 1990 and 2015 amounted to 8.5% of forest area 1990. Assuming that the same proportion of forest area is converted in the future, it was estimated that 11.5% of 2015 forest area would become grassland and shrubland by 2050 under BAU.

These projected changes in the extent of different land cover classes were used to set up the InVEST Scenario Generator: Proximity Based model. The model was run in a series of steps to generate the BAU land cover layer for 2050 (Figure 2), as described further in the methods section. The projected changes in land cover under BAU are shown and compared with 2015 and 1990 in Table 3. All natural habitats were predicted to decline in area from 2015 to 2050 under BAU, except for waterbodies which are summed to remain stable in area. Some of the most notable changes include a marked further reduction in forest cover due to the expansion of cropland and settlement and the degradation of forest to grassland and shrubland. As a result, remaining forest cover in 2050 was projected to be just 21% of forest area in 1990. Conversely, cropland increases further to cover 67% of Rwanda's land surface area by 2050. Settlement also expands significantly, almost doubling in area from 2015 to 2050.
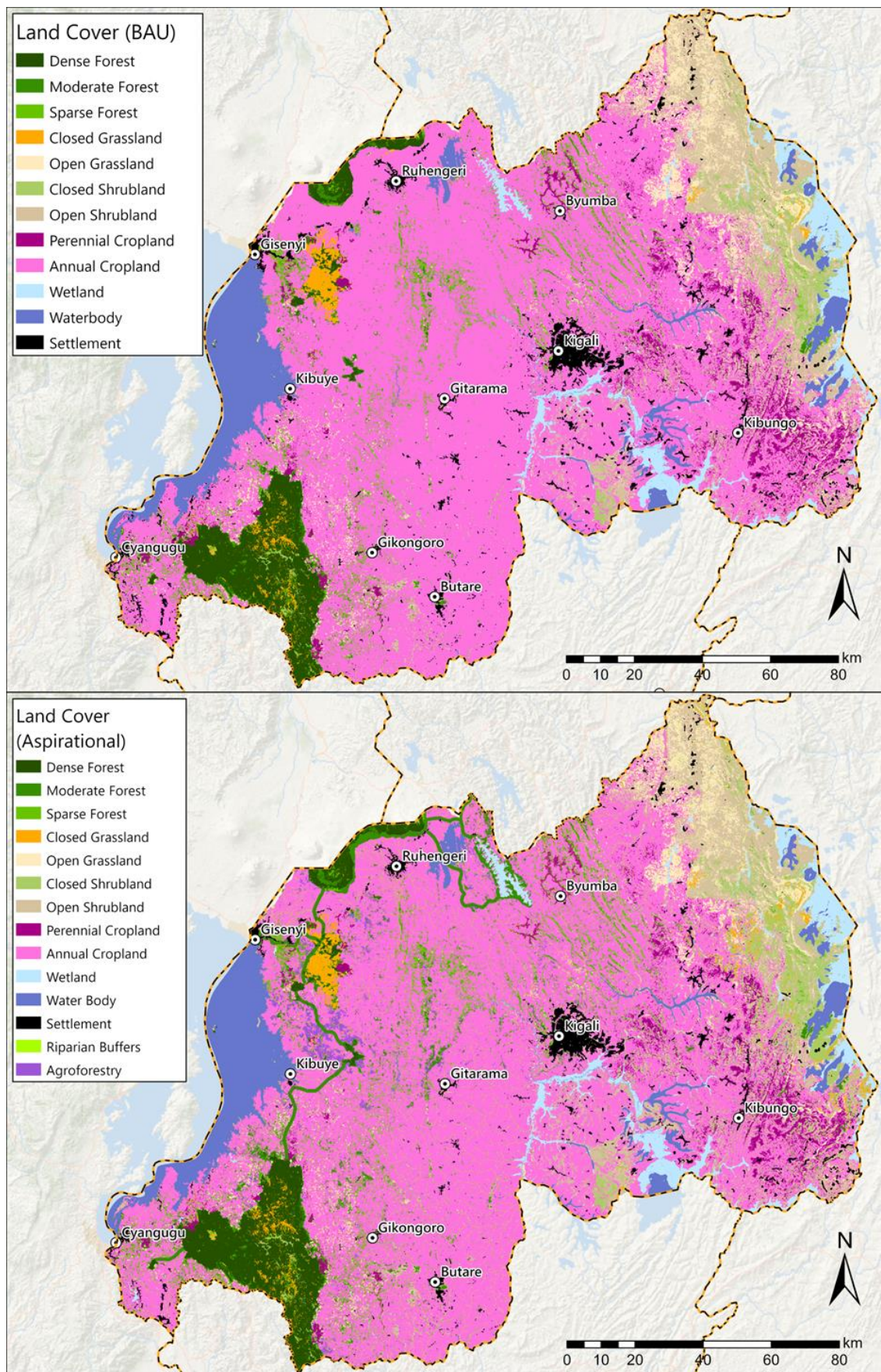
Figure 2. Comparison of projected land cover under the BAU Scenario (top) and Aspirational Scenario (bottom). Note that interventions like riparian buffers are too fine-scale to see on this national-scale map.

Table 3. Historical and projected extent of broad land cover categories.

Land cover class	Historical area (ha)		Projected area (ha)	
	1990	2015	2050 BAU	2050 ASP
Forest	1 089 390	432 577	229 799	334 274
Grassland	88 044	149 204	134 222	127 226
Shrubland	446 410	332 643	274 380	295 272
Cropland	624 221	1 344 952	1 598 495	1 489 881
Wetland	109 838	89 085	85 028	87 585
Waterbody	153 643	152 593	152 616	152 616
Settlement	11 633	36 344	61 869	49 569
Other land	3 560	590	589	574

The projected extent of the different broad land cover classes under the Aspirational Scenario is also shown in Table 3 and mapped in Figure 2. Since this scenario assumed that there would be continued expansion of agriculture and settlement, but in combination with improved efforts to protect and restore natural habitats, the land cover projections under the Aspirational Scenario largely fall somewhere between the current and BAU land cover projections. Forest cover was still predicted to decline under the Aspirational Scenario, but to a lesser extent than under the BAU scenario. The reduction in forest loss relative to BAU reflects various interventions, including the plans to expand Volcanoes National Park, establish new forest protected areas in other parts of the country, create forest corridors to improve forest connectivity in western Rwanda, reforest degraded forest areas mapped in the CROM DSS and install riparian buffers in place of streamside cultivation. However, collectively these interventions are still not enough to avoid further forest loss under the Aspirational Scenario, suggesting further measures are required if this is the goal. A similar trend is observed for shrubland. Grassland was projected to decline under the Aspirational Scenario relative to BAU. However, this is due to the restoration of grassland to forest or shrubland in areas where grassland represents degradation.

Cropland was still projected to expand under the Aspirational Scenario but by a smaller amount than under BAU (Table 3). This reflects the extra restrictions on cropland under the Aspirational Scenario, such as the prevention of farming in proposed protected areas, including wetlands gazetted for strict protection, as well as a reduction in cropland along watercourses with the addition of riparian buffers. There is also an inherent assumption that there will be some intensification of agricultural land use relative to BAU, in order to achieve the same level of production from a smaller area of cropland. These measures also contribute to the increase in wetland area under the Aspirational Scenario relative to BAU. Similarly, efforts to densify and constrain urban expansion to selected cities result in a significant reduction in the urban footprint relative to the BAU scenario. Nevertheless, it was assumed urban expansion could not be completely avoided under the Aspirational Scenario, especially given Rwanda's goal of attaining a 70% urbanisation level under its Vision 2050 national development plan (Republic of Rwanda, 2020).

4.2   Ecosystem Services Under Current and Future Land cover Scenarios

4.2.1   Carbon Retention

Under current land cover, it was estimated that woody vegetation in Rwanda stores 14.7 million tonnes of carbon as aboveground biomass (AGB) and a further 9.9 million tonnes as belowground biomass (BGB) (Table 4) giving a combined total of 24.6 million tonnes of biomass carbon. Given the

dominance of farmland, the average storage of biomass in carbon is relatively low, with a mean AGB carbon density estimate of 6.1t/ha and mean BGB carbon density of 4.1 t/ha (excluding waterbodies). As noted earlier, this is likely to be a conservative estimate of biomass carbon storage in the country, as the aerial imagery used by Mugabowindekwe *et al.* (2023) does not adequately capture the contribution of understorey trees, particularly in dense forest. A much greater amount of carbon is stored as soil organic carbon (SOC), estimated to be 213 million tonnes or an average of 89.4 t/ha (excluding waterbodies) across Rwanda. While this result is based on a global dataset rather than local estimates, soil carbon storage is typically much higher than biomass carbon storage in African ecosystems (Houghton & Hackler, 2006).

Across land cover classes, dense forest has the highest average carbon storage across the AGB, BGB and SOC pools (Table 4), with average biomass carbon storage in particular being several times higher than all other land cover categories. Despite covering just 5% of Rwanda's land surface area in 2015, dense forest accounts for just over half of total biomass carbon storage in the country, indicating its high importance as a carbon reservoir. Conversely, both annual and perennial cropland store little carbon biomass, with mean AGB storage of less than 3 t/ha and mean BGB storage of less than 1 t/ha. In contrast, cropland was estimated to have relatively high mean SOC storage, intermediate between higher SOC forest vegetation and the lower biomass estimates for most shrubland and grassland types. However, this is largely due to the disproportionate location of cropland in wetter parts of the country which naturally have higher levels of SOC, relative to drier grassland and shrubland areas in the west of the country. This is supported by the estimates provided by Houghton & Hackler (2006), where cropland in formerly moist forest areas typically have higher soil carbon biomass than undisturbed dry forest and shrubland ecosystems. Since the preferential location of cropland in areas with naturally higher SOC values would bias the results under future scenarios, the focus was on changes in biomass carbon only under future land use options. However, in both moist and dry areas, the conversion of natural ecosystems to cropland still typically results in a reduction in SOC relative to the undisturbed baseline (Houghton & Hackler, 2006).

Table 4. Total and average carbon storage across SERVIR land cover classes. AGB estimates derived from Mugabowindekwe et al. (2023), BGB calculated from AGB using root-shoot ratios *(IPCC, 2006, 2019)*, SOC derived from GSOC layer *(FAO & ITPS, 2018)*.

Land cover class	Total AGB carbon (t)	Average AGB carbon (t/ha)	Total BGB carbon (t)	Average BGB carbon (t/ha)	Total SOC (t)	Average SOC (t/ha)
Dense Forest	6 893 618	59.7	5 686 208	49.3	16 814 111	145.0
Moderate Forest	583 491	12.4	481 380	10.2	5 860 973	120.8
Sparse Forest	1 237 640	4.6	1 021 053	3.8	28 359 710	105.3
Closed Grassland	296 302	9.4	468 157	14.9	4 626 880	142.6
Open Grassland	338 328	2.9	534 558	4.6	7 688 117	64.9
Closed Shrubland	297 617	6.0	119 047	2.4	2 894 353	60.2
Open Shrubland	981 531	3.5	392 613	1.4	16 069 369	58.0
Perennial Cropland	68 033	2.0	18 305	0.5	2 922 988	85.2
Annual Cropland	3 532 719	2.7	950 514	0.7	117 003 435	90.2
Wetland	108 132	1.2	149 222	1.7	6 776 650	79.6
Water Body	263 601	1.9	0	0.0	1 758 092	74.7
Settlement	117 446	3.2	28 187	0.8	2 291 506	62.8
Other land	2 621	4.5	1 048	1.8	88 861	92.5
Overall	**14 721 077**	**6.1**	**9 850 292**	**4.1**	**213 152 203**	**89.4**

Under the BAU scenario, biomass carbon storage was predicted to decline by 1.7 million tonnes to 22.9 million tonnes relative to present levels, representing a 7% loss of current biomass storage (Table 5). The Aspirational Scenario results in a significant increase in carbon storage relative to BAU. Biomass **carbon storage was estimated to be 24.5 million tonnes under the Aspirational Scenario, representing a 1.6 million tonne or 7% increase over BAU**. Hence, under the Aspirational Scenario, biomass carbon storage in Rwanda remains at a similar level to current land cover, despite there still being an overall expansion of cropland and settlement. Since these carbon gains under the Aspirational Scenario are achieved largely through reducing deforestation and improving tree cover relative to BAU, this demonstrates the potential for the proposed interventions to generate revenue for Rwanda through REDD+ and other carbon credit schemes.

Table 5. Total biomass carbon storage (in tonnes) across land management scenarios.

Scenario	Total AGB carbon (t)	Total BGB carbon (t)	Total biomass carbon (t)
Current	14 721 077	9 850 292	24 571 369
BAU	14 010 901	8 897 656	22 908 557
Aspirational	14 804 624	9 696 019	24 500 640

4.2.2 SEDIMENT RETENTION AND SOIL EROSION CONTROL

Soil erosion is an issue of serious concern in Rwanda, and is identified as the single most serious environmental problem in many of the country's catchments in a recent report on erosion control measures in Rwanda (RWB & IUCN, 2022). Soil erosion raster under current land cover were estimated to be 25.3 t/ha/year across Rwanda overall. This figure is slightly lower than but comparable to the 34.2 t/ha/year estimated by Fenta *et al.*, (2020) using a similar USLE-based approach, and identical to the national average of 25 t/ha/year reported in the State of Soil Erosion Control in Rwanda report (RWB & IUCN, 2022). Of this soil, it was estimated that 3.1 t/ha ends up as sediment in watercourses, where it contributes to reduced water quality and reservoir sedimentation issues.

Table 6. Estimated current soil erosion and sediment export rates (in tonnes) across land cover classes.

Land cover class	Total soil loss (t/year)	Average soil loss (t/ha/year)	Total sediment export (t/year)	Average sediment export (t/ha/year)
Dense Forest	118 687	1.0	4 373	0.0
Moderate Forest	298 274	6.3	28 179	0.6
Sparse Forest	3 422 712	12.7	379 079	1.4
Closed Grassland	665 800	21.2	54 852	1.7
Open Grassland	1 267 177	10.8	126 592	1.1
Closed Shrubland	330 633	6.6	26 953	0.5
Open Shrubland	2 389 365	8.5	226 989	0.8
Perennial Cropland	446 676	13.2	45 906	1.4
Annual Cropland	54 235 534	41.5	6 804 931	5.2
Wetland	72 389	0.8	4 639	0.1
Water Body	6 702	0.0	394	0.0
Settlement	369 407	10.2	31 485	0.9
Other land	16 866	28.9	1 718	2.9
Overall	**63 640 224**	**25.3**	**7 736 089**	**3.1**

A breakdown of current estimated erosion and sedimentation rates by land cover class is given in Table 6. In both aggregate and per hectare terms, annual cropland has the highest rates of erosion and sediment export by some margin. Average erosion from perennial cropland was estimated to be somewhat lower, as it tends to have greater year-round vegetation cover. Dense forest was estimated to have very low erosion and sediment export rates, lower than any other terrestrial land cover type, despite typically being located in high rainfall, steep areas where erosion risk is high. Rwanda's largest remaining blocks of dense forest are found in Volcanos and Nyungwe National Park, both of which are situated at the top of watersheds that supply water to dense downstream human populations. The sediment control services provided by these forests are thus highly beneficial for watershed protection and reducing sediment-related issues in downstream watercourses (Republic of Rwanda, 2016).

Sediment export and sedimentation rates were predicted to increase under both future scenarios relative to current land cover, due to the expansion of cropland and settlement into natural land cover. However, larger increases were predicted for the BAU scenario, reflecting the greater extent of anthropogenic land cover types which have higher erosion and sediment export rates (particularly cropland; Table 7). The proposed interventions under the Aspirational Scenario are projected to **reduce annual soil erosion by 5.3 million** tonnes **relative to BAU, a reduction of 7%. The amount of eroded sediment reaching watercourses was also predicted to decline significantly by 1.2 million tonnes, an 11% reduction in sediment export relative to BAU.** The percentage reduction is larger for sediment export, as the overall reduction in erosion in the landscape means a higher proportion of eroded soil can be retained by downslope vegetation before it can reach watercourses.

Table 7. Comparison of soil erosion and sedimentation rates across land management scenarios.

Scenario	Total soil loss (t/year)	Average soil loss (t/ha/year)	Total sediment export (t/year)	Average sediment export (t/ha/year)
Current	63 640 224	25.3	7 736 089	3.1
BAU	75 982 780	30.2	10 680 096	4.2
Aspirational	70 695 928	28.1	9 510 915	3.8

Since this assessment focused on planned interventions with the explicit or implicit goal of benefitting biodiversity, measures to reduce erosion from cropland were limited to agroforestry and riparian buffers, with the assumption that both of these interventions would utilise at least a proportion of native plant species. However, cropland remains the major contributor to erosion and sedimentation under the future land cover scenarios. As a result, even under the Aspirational Scenario, the expansion of cropland contributes to the overall increase in erosion relative to current land cover, despite the range of proposed interventions under this scenario. While the reductions in erosion and sedimentation predicted under the Aspirational Scenario are notable relative to BAU, the more widespread application of improved erosion control measures on farmland (as mapped out in the CROM DSS, for example) would likely result in much larger reductions.

4.2.3 HABITAT QUALITY

High quality natural habitats are already scarce in Rwanda under current land cover, reflecting high human population densities and the dominance of agricultural land cover. Additionally, where forest and other "natural" land cover classes do remain outside of protected areas, they are often dominated by exotic species with low biodiversity value (Republic of Rwanda, 2019). The total habitat quality score in Table 8 is derived from summing all pixel-level habitat scores, thus reflecting both the total

extent and average quality score of remaining natural habitats in the country. The extensive habitat transformation that has already occurred in Rwanda is reflected in the low overall average habitat quality score for the country of 0.16. Considering that a value of 0 reflects habitat with no biodiversity value and a value of 1 reflects pristine natural habitat, the estimated habitat quality score highlights the extent to which natural habitats have been extensively transformed in the country, with a few main "islands" of higher quality habitat remaining inside protected areas.

Average habitat quality was projected to decline by 8% under BAU relative to current habitat quality (Table 8). Most of the land cover changes under BAU scenario occur outside of protected areas, where remaining natural habitat patches are already generally small with low habitat quality, thus their transformation makes only a modest contribution to further declines in habitat quality.

The interventions under the Aspirational Scenario result in an **improvement in habitat quality over both the BAU scenario and current land cover, with an increase of 19% relative to BAU**, and an improvement of 9% relative to current land cover (Table 8). It is notable that the interventions result in an overall improvement in habitat quality relative to current land cover, despite the further expansion of cropland and settlement under this scenario. Nevertheless, the overall average habitat quality score of 0.18 is still low, reflecting the fact that cropland remains highly dominant at the expense of natural habitats, with most of the country thus having low biodiversity value.

Table 8. Estimated habitat quality across scenarios, with percentage differences in quality relative to BAU land cover.

Scenario	Total Habitat Quality	Mean Habitat Quality/pixel	% difference relative to BAU
Current	415 614	0.16	8%
BAU	381 413	0.15	-
Aspirational	454 572	0.18	19%

5   CONCLUSION

Rwanda has lost 60% of its forest cover in the last 35 years, with forest now covering just 18% of the land area. It also lost 19% of its wetland are over the same period. As the most densely-populated country in Africa, the country is now dominated by modified habitats with low biodiversity value. Under a BAU scenario, it is projected that country will lose half of its remaining forest area as a result of agricultural and urban expansion, leading to further declines in habitat quality, biodiversity and water quality, and increased risks of sedimentation, landslides and floods. Under an Aspirational Scenario, a large proportion of these losses could be averted. Relative to the BAU Scenario, some 1.6 million more tonnes of carbon (7% more) would be retained, the amount of sediments entering water courses every year would be 1.2 million tonnes (11%) lower, and habitat quality for biodiversity would be 19% better.

Despite the limited capacity for changing Rwanda's environmental trajectory due to its high population density and advanced level of habitat transformation, it is encouraging that the various interventions proposed under the Aspirational Scenario result in notable increases in the delivery of all three selected ecosystem services (carbon retention, soil erosion and sedimentation control and habitat quality) relative to BAU. While the Aspirational Scenario represents an ambitious plan to restore the landscape, an effort was made to ensure interventions were limited to those that might be feasible, and in line with proposals that have been made by various local authorities. Nevertheless, given the degree of habitat transformation that has already occurred and the likely need to relocate large numbers of people, many of these interventions would require substantial investment and restoration effort, particularly in the wet formerly forested parts of the country. For example, the initial proposed expansion of Volcanos National Park by 1081 ha will require the relocation of 1109 households, even though the expansion area amounts to just 0.05% of Rwanda's surface area. Undertaking such interventions at a large-scale is unlikely to be economically or socially feasible.

Given the difficulty and cost of undertaking large-scale restoration in Rwanda once habitat transformation has occurred, preventing the further loss of indigenous habitats should be seen as the first priority. These areas are critical refugia for globally-valuable biodiversity and have very high marginal value in terms of the supply of ecosystem services (Turpie *et al.*, 2021). Reducing the pressure to convert natural habitats in the face of future population growth will require more spatially efficient urbanisation and the intensification of agricultural land use, as well as increased adoption of alternative fuel sources to firewood and charcoal. In combination with restoration where feasible, these measures can help reduce the degradation of ecosystem services in Rwanda relative to business-as-usual.

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