LULUCF Emission Factor Database, Updated Inventory and Projected Baseline

ICAT Initiative for Climate Action Transparency

Initiative for Climate Action Transparency – ICAT

LULUCF emission factor database, updated inventory and projected baseline

Deliverable # (Deliverables 2 and 3 of Activity 4)

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ABBREVIATIONS

AFOLU	Agriculture, Forestry and Other Land Use
DOM	Dead Organic Matter
ESWADE	Eswatini Water and Agricultural Development Enterprise
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land Use Change and Forestry
QA/QC	Quality Assurance/Quality Control
SOC	Soil Organic Carbon

EXECUTIVE SUMMARY

The aim of this analysis was to develop an emissions factor database as well as making baseline estimates and projections for the Land Use, Land Use Change and Forestry (LULUCF) sector in Eswatini. The emission factors were sourced from local and regional (mainly South African) literature as well as local spatial datasets. The database was created as a spreadsheet for ease of use in future inventory updates.

The LULUCF inventory includes the emissions of carbon dioxide (CO_2) from changes in land use between the period 1990 and 2020. It included the biomass, dead organic matter (DOM) and soil organic carbon (SOC) changes. Emissions were estimated using the Intergovernmental Panel on Climate Change (IPCC) 2006 guideline methodologies. The Gain-Loss approach was used as was the case in the previous inventory. The land area activity data was described in the first deliverable for Activity 4, biomass burning data was obtained from remotely sensed data and other ancillary data for plantations and croplands was sourced from both the public and private sector. The harvest volume for plantations was obtained from FAOSTAT data due to a lack of country specific data. All data was quality checked and verified through consultations with various stakeholders in the agriculture, forestry and land use sectors to ensure consistency and validity.

Baseline projections were estimated for the period 2021 to 2050. Land area projections were based on annual average land change areas between 2005 and 2020, while projected cropland area was based on historical cropland area data. Plantation harvest volume was projected based on a linear trend in the data between 2005 and 2020. Burnt area and fuelwood collection data was projected using historical multi-seasonal trends and projected demographic changes, respectively.

The emissions in 2020 are estimated at **1,635.28 Gg CO_2e** with wood removals from timber plantations and this changes to a net sink of **-1,905.51 Gg CO_2e** without timber plantation wood removals. Similarly, when excluding biomass burning, the emissions drop to **950.85 Gg CO_2e in 2020** and when both timber plantation wood removals and biomass burning are excluded, net removals of **-2,589.94 Gg CO_2e** is observed. These findings highlight the significant impacts of timber harvesting and biomass burning on the LULUCF sector's emissions profile. The results also point to a declining forest sink that will continue to decline for the foreseeable future due to conversion to other land uses such as cropland and human settlements. The key sources of emissions are fuelwood removals, land converted to cropland, and biomass burning. The trends in these sub-categories are also expected to drive the projected increases in emissions up to 2050. This suggests the need for responsive energy policies to reduce the over-reliance on fuelwood as well as fire management policies and programmes to reduce unwanted and unmanaged forest fires. Expansive agricultural development programmes need to be reviewed within the context of sustainable land management and land use planning.

There was significant improvement in the data applied in this inventory compared to the previous (2018) inventory, such as annual land change maps, additional land categories, improved forest and sugarcane plantation data and enhanced soil carbon data. Recommendations are then provided to ensure continual improvement and progression towards a full Tier 2 approach, and possible Tier 3 estimates in future.

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1. INTRODUCTION

The Agriculture, Forestry, and Other Land Use (AFOLU) sector plays a crucial role in Eswatini's economy as well as in climate change mitigation and adaptation. Plants take up carbon dioxide (CO_2) from the atmosphere and nitrogen (N) from the soil when they grow, re-distributing it among different pools, including above and below-ground living biomass, dead residues, and soil organic matter. The CO_2 and other non-CO_2 greenhouse gases (GHG), largely methane (CH_4) and nitrous oxide (N_2O), are in turn released to the atmosphere by plant respiration, by decomposition of dead plant biomass and soil organic matter, and by combustion. Anthropogenic land-use activities (e.g. management of croplands, forests, grasslands, wetlands) and changes in land use/cover (e.g. conversion of forest lands and grasslands to cropland and pasture, and afforestation) can cause changes superimposed on these natural stocks and fluxes. Hence, AFOLU activities lead to both sources of CO_2 (e.g. deforestation and peatland/wetland drainage) and sinks of CO_2 (e.g. afforestation and management for soil carbon sequestration), and to non-CO_2 emissions primarily from biomass burning.

The Land Use, Land Use Change and Forestry (LULUCF) or FOLU sub-sector is different from the other sectors (i.e., waste, transport, energy and industry) in that the mitigation potential is derived from both an enhancement of removals of greenhouse gases (GHG), as well as a reduction of emissions through management of land. Eswatini's desire to transition towards a low carbon economy underscores the need to explore various mitigation options. There are several supply and demand options for mitigation in this sub-sector. On the supply side emissions can be reduced from land use change and land management while terrestrial carbon stocks can be enhanced by sequestration in soils and biomass. On the demand side emissions can be reduced through changing consumption patterns. During the most recent inventory (Government of Eswatini, 2020), Eswatini improved the quantification of AFOLU emissions and the understanding of the dynamic relationship between sinks and sources through adopting the 2006 IPCC Guidelines, a significant step away from the previous inventory which utilized the 1996 guidelines.

However, despite the recent improvements in the GHG estimation, key improvements were identified in order to reduce the uncertainties of the estimates. Most of the emission factors used in the GHG inventory were also the default IPCC values. In addition, the IPCC software used could only use Tier 1 methods. This indicated that the Eswatini emissions baseline (current or projected) against which the mitigation potentials can be measured had relatively high uncertainties and gave an incomplete picture of the country's mitigation potential. A well-developed baseline, more specifically a projected baseline, has the advantage of enabling Desired Emissions Reductions Outcomes (DEROs) and Carbon Budgets to be determined for the AFOLU sector. In addition, it will allow Eswatini to demonstrate its contribution towards the global goal of reducing emissions from the AFOLU sector.

This report, therefore, presents the methodology used in creating the emission factor database for the LULUCF sector as well as outputs/findings from the updated LULUCF inventory (1990 – 2020) and the baseline projections (2021-2050).

2. SCOPE OF WORK

2.1 Objectives

This report serves as an addendum to the report on "Improved land use change maps and annual change methodology" (Dlamini, 2022). Specifically, this report focuses on the following:

- Creating and updating a country specific LULUCF emission factor database.
- Creating an updated LULUCF inventory and projected baseline.

3. METHODOLOGY

3.1 Development of emission factor database

Stakeholders and different sectors are increasingly showing an interest in carbon accounting and use tools that are suitable to their context and scale. As such, several methodologies and tools for quantitative estimates of greenhouse gas (GHG) emissions have been developed by international organizations, among them ISO 14064, and the IPCC and other GHG Protocols. The Intergovernmental Panel on Climate Change (IPCC) provides guidelines which outline methodologies for estimating national inventories of anthropogenic emissions by sources and removals by sinks of greenhouse gases. The IPCC has so far developed:

- the Revised 1996 Guidelines for National Greenhouse Gas Inventories, IPCC (1997), known as the "1996 IPCC Guidelines",
- Good Practice Guidance and Uncertainty Management, IPCC (2000), known as the "GPG2000",
- Good Practice Guidance for Land-Use, Land-Use Change and Forestry, IPCC (2003) known as the "GPG-LULUCF",
- the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IPCC (2006) known as the "2006 IPCC Guidelines",
- 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands known as the "Wetlands Supplement", and
- the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories known as the "2019 Refinement".

These methods are all based on the same approach using GHG emission factors. Emission factors are the base of any calculation method, so it is important to use standardized values at national level. Many countries do not have their own national emission factor databases and use international standards (predominantly IPCC) or other values. These international standards do not always correspond to real-life activities in the countries and regions where the GHGs are estimated. The creation of a national database of emission factors for the LULUCF/FOLU sector is a significant step towards providing and sharing reliable and Eswatini-specific data among public (and private) institutions for the purpose of understanding the country's GHG emissions trajectory as well as for developing the country's low carbon strategy.

The emission factor database is not only a compilation of emission factors but will also increase the awareness and competence of local actors and stakeholders regarding land use and climate issues, and foster the emergence of an ecosystem of teaching materials, training programmes, tools and methods for establishing local climate plans, transition strategy for organizations, etc. Under the auspices of the Ministry of Tourism and Environmental Affairs (MTEA) – the entity that will administer and manage the emission factor database – there is need to ensure the ongoing vitality of the database. This must be updated as new data from research studies is availed.

Subsequently, a national emission factor database containing more than 300 emission factors for different land uses, soils and climate zones were created. The emission factor database contains factors such as growth rates, carbon content of wood, conversion of above ground biomass to total biomass, biomass factors and stock change factors. These were obtained from extensive review of both Eswatini and regional (predominantly South African) literature. Effort was put in ensuring that the emission and biomass factors were published in peer-reviewed journals and were from reputable and/or authoritative sources such as government and industry reports, technical studies, etc. Whilst there were very few Eswatini literature, some of the factors were derived from an analysis of local and South African datasets such as biomass and soils datasets. The datasets were integrated into ArcGIS Pro 2.9 and overlay analysis performed. The land use, climate and soil classification maps were overlayed to determine the soil carbon value for each soil and climate type.

South African land uses, ecosystems and the climates are very similar to those of Eswatini and as such those were preferred over the IPCC default values. The updated South African National Terrestrial Carbon Sinks Assessment 2020 was used to derive some of the biomass factors. The South African National Carbon Sink Assessment was a nationwide assessment of terrestrial carbon stocks and fluxes as well as an exercise aimed at evaluating all climate change mitigation opportunities within the AFOLU sector. Soil organic carbon factors, on the other hand, were derived from local studies and datasets and as such represent local conditions.

3.2 GHG Inventory

3.2.1 GHG emission estimation

The methodology for calculating the emissions followed the IPCC 2006 guidelines (IPCC, 2006). The Gain-Loss methodology was selected for biomass carbon as a there is no national forest inventory and carbon stock data is lacking. For DOM the Tier 1 IPCC default assumption of no change for land remaining land was assumed, while the stock difference approach was applied (IPCC 2006 Equation 2.19) for land conversions (IPCC, 2006).
The inventory included emissions from:

- Forest lands:
  - Forest remaining forest
  - Land converted to forest
- Croplands:
  - Croplands remaining croplands
  - Land converted to croplands
- Grasslands:
  - Grasslands remaining grasslands
  - Land converted to grasslands
- Settlements:
  - Settlements remaining settlements
  - Land converted to settlements
- Other lands:
  - Other lands remaining other lands
  - Land converted to other lands

The 20-year default period was applied for land conversions, therefore annual change area and accumulated (over the 20-year period) areas were determined in the emission calculation file. The annual change area was utilised to determine biomass changes for converted lands, while accumulated area was used in the DOM and SOC calculations as these carbon pools accumulate over time. Soil organic carbon (SOC) calculations were done with an Approach 2 and a Formulation B of Equation 2.25.

Forest lands consisted of indigenous forests and forest plantations. Forest plantations were further sub-divided into wattle, pine and Eucalyptus. Croplands had the sub-categories of rainfed croplands (majority being maize), irrigated cropland (majority being sugarcane) and tree croplands. Tree crops is a new category that was not previously included, and these would be fruit crops such as citrus fruits, bananas, Macadamia, among others. The data sources are shown in Table 1.

The Intergovernmental Panel on Climate Change (IPCC) refers to three general tiers for estimating emissions/removals of GHGs. The tiers represent different levels of methodological complexity:

- Tier 1 is the basic method
- Tier 2 uses country-specific data
- Tier 3 is the most demanding in terms of complexity and data requirements

This study attempted to use Tier 2 methods as much as practically possible for the measurement of significant carbon sinks/emission sources. The Tier 2 methods use the same methodological approach as Tier 1 but country- or region-specific data emission and stock change factors were applied for the most important land use categories particularly the cropland and forestland. The country-defined emission factors were more appropriate for Eswatini-defined climatic regions, soil types and land-use systems. The higher temporal (annual) and spatial resolution (30m) and more disaggregated activity data that were produced in the land use mapping exercise (see Deliverable 1 report) make it possible to use Tier 2 methods to correspond with country-defined or region-specific coefficients for key land use categories (Table 2).

Table 1: Land use categories assessed and their data sources.

	Land use category	Data sources
Land area	Forest land	Remote sensing analysis (see Deliverable 1 report), timber companies and Department of Forestry
	Cropland	Remote sensing analysis (see Deliverable 1 report), Eswatini sugar association, sugarcane companies
	Grasslands	Remote sensing analysis (see Deliverable 1 report)
	Wetlands	Remote sensing analysis (see Deliverable 1 report)
	Settlements	Remote sensing analysis (see Deliverable 1 report)
	Other land	Remote sensing analysis (see Deliverable 1 report)
	Other data	
Soil organic carbon (estimated for each land use category)	SOC estimated from soils map of Eswatini using local field datasets (modelled) – see FAO (2022). Global Soil Organic Carbon Map – GSOCmap v.1.6. Technical report. Rome. https://doi.org/10.4060/cb9015en	
Biomass burning	Moderate Resolution Imaging Spectroradiometer (MODIS) MCD64A1 Collection 6 burned area data	
Fuelwood harvesting	Estimated from estimated per capita consumption values of firewood by Ngwenya and Hassan (2005).	

Table 2: Tiers used in the GHG estimation for the LULUCF sector.

IPCC code	Land use	Biomass	DOM
3B	Total land		
3B1	Forest land		
3B1a	*Forest land remaining forest land*	*Tier 2*	*Tier 1*
3B1b	*Land converted to forest land*	*Tier 2*	*Tier 1*
3B2	Cropland		
3B2a	*Cropland remaining cropland*	*Tier 2*	*Tier 1*
3B2b	*Land converted to cropland*	*Tier 2*	*Tier 1*
3B3	Grassland		
3B3a	*Grassland remaining grassland*	*Tier 1*	*Tier 1*
3B3b	*Land converted to grassland*	*Tier 2*	*Tier 1*
3B5	Settlements		
3B5a	*Settlement remaining settlement*	*Tier 1*	*Tier 1*
3B5b	*Land converted to settlement*	*Tier 2*	*Tier 1*

3B6	Other lands		
3B6a	*Other land remaining other land*	*Tier 1*	*Tier 1*
3B6b	*Land converted to other land*	*Tier 2*	*Tier 1*

All land use areas were divided by climate, soil type and eco-region. Emission factor for the different eco-regions is not known so this division did not have an impact but was kept so in future additional data can be collected and added as the inventory develops. The climate and soil type was used to determine the reference SOC value and the stock change factors (IPCC default values were applied). The file for each climate and soil type was created where the SOC change data was determined. This was then aggregated into one file for national SOC change per land category (both land remaining and land converted) and then pulled into the overall calculation file. An inventory calculation file was setup containing all the relevant IPCC equations. This calculation file contained all the sub-category files, sub-category summary pages, a national summary page, and some initial sheets for conversions factors and land areas (Table 3). The emission factor database was also incorporated into the calculation file.

Table 3: List and description of the worksheets in the inventory calculation file.

Worksheet name	Description
QA Log	A Quality Assessment log which uses a tagging system to aid documentation and QAQC processes, increasing efficiency and transparency. Tags are also added to a document by the users and are then collated by the tool into one table.
LC codes	This sheet contains the land use codes as derived from the spatial (raster) data. This can be used to interpret the raster data when read with GIS/mapping software.
Annual LC	This sheet contains the activity data indicating the area of each observed land use change category. The data is provided for each year from 1990 to 2020 as well as the projected data from 2021 to 2050.
Change matrix	This sheet contains the land use change matrix for the period used to make the projections to 2050. In the default case, this is from 2005 to 2020 but this can be modified as and when required.
Constants and emission factors	This sheet contains the constants, emission and biomass factors used in the Eswatini inventory. A separate emission factor database is also provided for reference.
References	This sheet provides a list of the references used in the compilation of the constants, emission and biomass factors.
LULUCF Summary	This sheet is a summary of the entire inventory and provides a snapshot of all the categories and sub-categories combined.
Land category summary pages (i.e. FL summary, CL summary, GL summary, SL summary, OL summary)	These pages show the overall summary for each of the land categories, showing the changes in biomass, DOM and SOC in the land remaining and the land conversion areas.
Land remaining land pages (i.e. FLrFL, CLrCL, GLrGL, SLrSL, OLrOL)	These pages show the calculation of carbon changes in biomass, DOM and SOC in land remaining land for each land category.
Land conversion pages (LcFL, LcCL, LcGL, LcSL, LcOL)	These pages show the calculation of carbon changes in biomass, DOM and SOC in the converted lands for each land category.
Burnt area	This sheet contains the activity data on burnt areas for each applicable land use category (both baseline and projected)
Fuelwood use	This sheet contains the activity data on fuelwood use (both baseline and projected)

Plantation data	This sheet contains reported planted area data from the Department of Forestry as reported from individual timber companies.
Sugarcane data	This sheet contains the data as reported by the Eswatini Sugar Association. Specifically, this includes area planted and area harvested as well as other ancillary biomass-related data.

The calculation sheet was colour coded to make quality control and review easier and also incorporate columns for the reference sources for all input data (see example in Figure 1). Notes and details of the IPCC equations utilised are also included in the calculation file to increased transparency.

Forest land emissions/removals SUMMARY

Total forest land summary

Lookup	IPCC code	Description	Gas	Unit	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
	3B1	**Forest land**	**CO2**	**Gg CO2**	**172.00**	**550.35**	**393.84**	**-109.13**	**57.69**	**-329.67**	**2,093.70**	**1,861.29**	**-170.25**	**843.14**	**848.97**
	3B1a	Forest land remaining forest land	CO2	Gg CO2	172.00	550.35	393.84	-109.13	57.69	-329.67	2,093.70	1,861.29	-170.25	844.12	847.33
	3B1b	Land converted to forest land	CO2	Gg CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.98	1.64
	3B1bi	*Cropland converted to forest land*	*CO2*	*Gg CO2*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*-0.75*	*-7.01*
	3B1bii	*Grassland converted to forest land*	*CO2*	*Gg CO2*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*-0.03*	*11.81*
	3B1biii	*Wetland converted to forest land*	*CO2*	*Gg CO2*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*-0.16*	*1.37*
	3B1biv	*Settlement converted to forest land*	*CO2*	*Gg CO2*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*-0.04*	*-4.49*
	3B1bv	*Other land converted to forest land*	*CO2*	*Gg CO2*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*-0.04*
		Calculation check			*TRUE*	*TRUE*	*TRUE*	*TRUE*	*TRUE*	*TRUE*	*TRUE*	*TRUE*	*TRUE*	*TRUE*	*TRUE*

Forest land remaining forest land

Lookup	IPCC code	Description	Gas	Unit	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
	Biomass gains														
IFIF	3B1a	Indigenous forest remaining indigenous forest	CO2	t C	641,679.74	641,679.74	641,679.74	641,679.74	641,679.74	641,679.74	641,679.74	641,679.74	641,679.74	641,662.35	640,247.77
PLPL	3B1a	Forest plantation remaining forest plantation	CO2	t C	594,754.56	594,754.56	594,754.56	594,754.56	594,754.56	594,754.56	594,754.56	594,754.56	594,754.56	594,732.73	575,723.46
PLIF	3B1b	Forest plantation converted to indigenous forest	CO2	t C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.39	439.43
IFPL	3B1b	Indigenous forest converted to forest plantation	CO2	t C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	378.78
	Biomass losses														
IFIF	3B1a	Indigenous forest remaining indigenous forest	CO2	t C	432,508.40	554,459.07	444,786.21	352,320.66	406,697.59	314,406.64	648,809.85	558,574.90	380,767.63	629,872.81	524,159.95
PLPL	3B1a	Forest plantation remaining forest plantation	CO2	t C	850,836.07	832,069.94	899,058.40	854,350.90	845,471.36	832,117.84	1,158,633.20	##########	809,234.67	836,458.93	848,545.09
PLIF	3B1b	Forest plantation converted to indigenous forest	CO2	t C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IFPL	3B1b	Indigenous forest converted to forest plantation	CO2	t C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	ΔC conversion														
IFIF	3B1a	Indigenous forest remaining indigenous forest	CO2	t C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PLPL	3B1a	Forest plantation remaining forest plantation	CO2	t C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PLIF	3B1b	Forest plantation converted to indigenous forest	CO2	t C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-254.28	-46,418.70
IFPL	3B1b	Indigenous forest converted to forest plantation	CO2	t C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-24,493.26

... | LULUCF summary | FL summary | FLrFL | LcFL | CL summary | CLrCL | LcCL | GL summary | GLrGL | LcGL | SL summary | SLrSL | LcSL | ...

Figure 1: An example of a spreadsheet in the calculation file.

It is worth mentioning that there exist opportunities for moving towards Tier 3 estimates for the forestland plantations and irrigated cropland sub-categories owing to the existence of detailed datasets within the various companies. During consultations with various stakeholders, it was evident that detailed activity data to undertake Tier 3 level analysis exists, however this data is dispersed between the various companies with varying levels of accessibility. A concerted effort needs to be made to establish an institutional structure for collecting and collating such data. Through this project, the Department of Forestry was assisted in developing a data collection template for data required for the inventory as they were in the processes of setting up a system to collect data from companies. Guidance and feedback were provided on their existing templates to include additional data that would be required for the inventory. Further institutional arrangements are required to set up a sustainable data collection and archiving framework.

3.2.2 QA/QC and verification

Underpinning the entire inventory were quality assurance and quality control (QA/QC) to ensure high-quality outputs that meet the international and national reporting requirements. Hence, the following quality elements were considered throughout the process as provided in the IPCC Guidelines:

- Transparency – comprehensive and clear documentation
- Completeness – inventory included all present sources and sinks
- Comparability – inventory used international reporting methods and formats
- Consistency – inventory used methods and data consistently across years
- Accuracy – inventory minimised over- and under-estimates of emissions

Systematic quality control activities were carried out in order to ensure completeness and consistency in the time series and correctness in the sum of sub-categories; where possible, activity data comparisons among different sources were made. For example, sugarcane and timber plantation area data from the remote sensing analysis were compared with official data. Data entries were also checked several times during the compilation of the inventory; particular attention was paid to the categories showing anomalous changes in succession. The land use matrices were checked and cross-checked to ensure that data were properly reported. Several QA activities were also carried out in the different phases of the inventory process. In particular, the applied methodologies were presented and discussed during several stakeholder workshops and expert meetings, collecting findings and comments to be incorporated in the estimation process.

3.3 Projection methodology

Land use and emissions projections were made for the period from 2021 to 2050. The projection of activity data was executed using two main techniques:

- Modified trajectory – projection of the future land use was based on the existing trajectory (historical data) particularly the period from 2005 to 2020 and linearly projected to reflect the expected changes as determined by current independent drivers, agents or causes such as demographic changes, development plans and agricultural policies (see Deliverable 1 report). This technique is much less complex than the modelling technique, while still integrating the effects of expected changes in the factors influencing the variable.

- Modelling – projection of future values of the variable based on a function or model which integrates the impacts of multiple drivers, agents and causes on the variable. This technique was highly data intensive, since it required enough data on past land use changes and changes in drivers, agents and causes to determine the causal relationships within the system. Whenever this technique was used, the data on past land use was used to develop and validate the model. For instance, fire activity tends to be driven by climate and solar (sunspot) cycles and as such 11-year cycles trend were assumed for the burned area data and this was to estimate future burned area. Similarly, the fuelwood usage was projected based on projected demographic (population) data from the Central Statistics Office.

The base year for the projections was revised from 2018 used in the most recent inventory to 2020 as this was the final date of the land change map. Hence, projections were made based on the land use in this year. The assumptions made above were also validated with stakeholders through individual consultations and workshops conducted as part of this exercise.

4. RESULTS

4.1 Emission factor database

The database, which accompanies this report, was developed as a Microsoft Excel spreadsheet and contains all the emission and biomass factors as well as the references/sources of values used (see Figure 2 below). This format and medium of the emission factor database were chosen as appropriate to the local context, as being accessible and easily readable. If a new emission factor database is being developed, as opposed to updating an existing one, scientific and technical expertise is needed to supply data based on calculated emissions factors, those drawn from the literature, etc. The methodology for determining emission factors (scope, assumptions, etc) focused on ensuring that these are reliable and consistent with database requirements such as accessibility, adaptability and traceability. While the technical features of any emission factor database are often the focus, experience from elsewhere shows that proper governance is the key factor for successful development and maintenance of an emission factor database. Hence, the database needs to be properly archived and be easily updated as well as being accessible to those who might need it.

CONSTANTS and EMISSION FACTORS

Conversion factors

Lookup	Factor description	Units	Value	Data source reference	Notes
	C to CO2		-3.667		
	Ton to Gg		0.001		
	Gg to ton		1,000.00		

GWP

Lookup	Factor description	Units	Value	Data source reference
	CH4		28.00	*IPCC AR5*
	N2O		265.00	*IPCC AR5*

Biomass factors

Lookup	Factor description	Units	Value	Data source reference
	Above ground biomass			
	Indigenous forests	t C/ha	30.60	*National Terrestrial Carbon Sinks Assessment: Technical Report (2020), Department of Environment, Forestry and Fisheries, Pretoria, South Africa*
	Forest plantation	t C/ha	89.90	*National Terrestrial Carbon Sinks Assessment: Technical Report (2020), Department of Environment, Forestry and Fisheries, Pretoria, South Africa*
	Wattle	t C/ha	57.15	*Dovey et al (2021) (Converted t dm/ha to t C/ha by multiplying by the IPCC default factor of 0.47)*
	Pine	t C/ha	44.55	*Dovey et al (2021) (Converted t dm/ha to t C/ha by multiplying by the IPCC default factor of 0.47)*
	Eucalyptus	t C/ha	45.00	*Dovey et al (2021) (Converted t dm/ha to t C/ha by multiplying by the IPCC default factor of 0.47)*
	Rainfed cropland	t C/ha	11.28	*National Terrestrial Carbon Sinks Assessment: Technical Report (2020), Department of Environment, Forestry and Fisheries, Pretoria, South Africa*
	Irrigated cropland	t C/ha	15.75	*Biomass value calculated from biomass data supplied by the Eswatini Sugar Association (see "Sugarcane data" sheet) using an an average cycle of 1 year (=58.85 t dm/ha), then converted to t C/ha using IPCC default factor of 0.47.*
	Tree cropland	t C/ha	18.84	*National Terrestrial Carbon Sinks Assessment: Technical Report (2020), Department of Environment, Forestry and Fisheries, Pretoria, South Africa*
	Grasslands	t C/ha	5.32	*Palmer et al. (2010)*
	Wetland	t C/ha	9.04	*National Terrestrial Carbon Sinks Assessment: Technical Report (2020), Department of Environment, Forestry and Fisheries, Pretoria, South Africa*
	Waterbody	t C/ha	0.00	*Assumed to be zero*
	Settlements	t C/ha	9.77	*National Terrestrial Carbon Sinks Assessment: Technical Report (2020), Department of Environment, Forestry and Fisheries, Pretoria, South Africa*
	Other land	t C/ha	0.13	*National Terrestrial Carbon Sinks Assessment: Technical Report (2020), Department of Environment, Forestry and Fisheries, Pretoria, South Africa*

Figure 2: Part of the emission factor database produced in this study.

4.2 Emission trends: 1990 – 2020

4.2.1 Overall trends

The LULUCF sector emissions includes carbon stock gains and losses and GHG emissions from all the land uses under consideration. Overall, the LULUCF sector is a net source of emissions almost throughout the entire time series (Figure 3). A total of **1,635.28 Gg CO_2e** were emitted in 2020 as a result. The trend indicates an increasing emissions scenario largely attributed to wood removals, land converted to cropland, and biomass burning. There are, however, interannual variations in the emissions largely attributed to annual variations in land use change and disturbance due to fire. For instance, a peak emission of 4,194.34 Gg CO_2e in 2019 is notable. The key sources of emissions are:

- Land converted to cropland
- Biomass burning
- Fuelwood removals

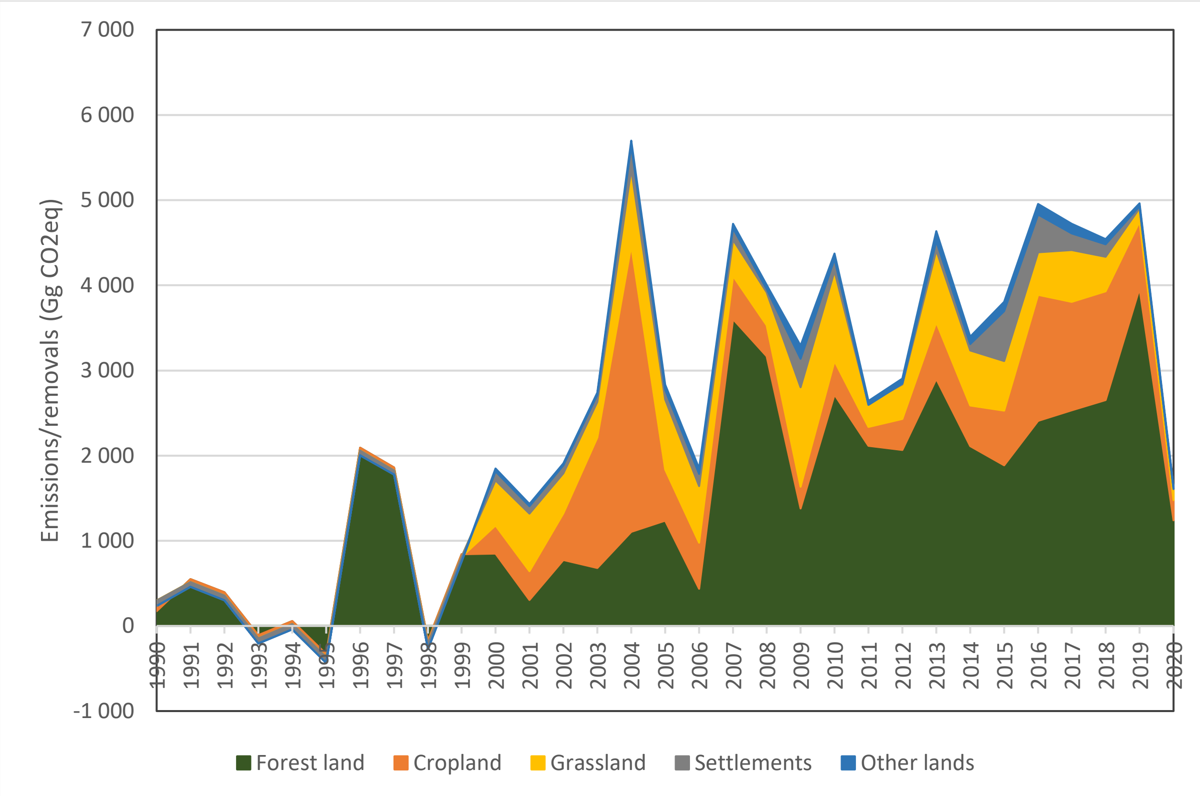


Figure 3: GHG trajectory from the LULUCF sector: 1990-2020.

The contribution of firewood is also notable but increasing constantly over time as a majority of Emaswati still rely on firewood for heating and cooking energy. As similarly observed in the 2018 GHG inventory, however, forest remaining forest and land converted to forests land is responsible for most of the CO_2 removals in the sector although it is declining sink across the time series. It is evident though that the forest sink is generally declining across the time series and will continue to do so for the foreseeable future. The reason for the decline in the carbon sink is directly linked to the drivers of forest conversion more specifically the conversion to commercial (irrigated) cropland, subsistence (rainfed) farming and harvesting for wood removals to produce timber. These are discussed in the report on Improved land use change maps and annual change methodology. Emissions, which start to accelerate from the early 2000s, are also contributed by croplands and grasslands. The contribution of cropland to emissions is mainly due to the conversion of indigenous forestland to sugarcane (irrigated cropland) which accelerated since the turn of the 21st century after the establishment of the Eswatini Water and Agricultural Development Enterprise (ESWADE) and subsequent agricultural projects. The contribution of grassland is mainly through biomass burning which is more prevalent and frequent in grasslands.

When excluding the wood removals from timber plantations, the sector becomes a net sink of **-1,905.51 Gg CO_2e in 2020**. This highlights the significant impact of wood removals from timber plantations on the country's GHG profile. This, therefore, points to the need for more detailed and accurate data on harvesting from the timber companies as FAOSTAT data was used in this analysis. The FAOSTAT is sometimes based on estimates which might not be reflective of the actual forestry product statistics. Furthermore, fuelwood removals are also a significant source of emissions comprising almost half (**821.69 Gg CO_2e**) of the emissions in 2020 (Figure 4). This is from **568.02 Gg CO_2e** in 1990 which increases linearly with human population.

Nevertheless, the impacts of the forest fires can still be seen particularly the 1997/1998 fires. Even when the wood harvesting from timber plantations is excluded, the forest sink continues to decline steadily with time. This is largely the result of the continuous decline of the indigenous forestland as previously highlighted.

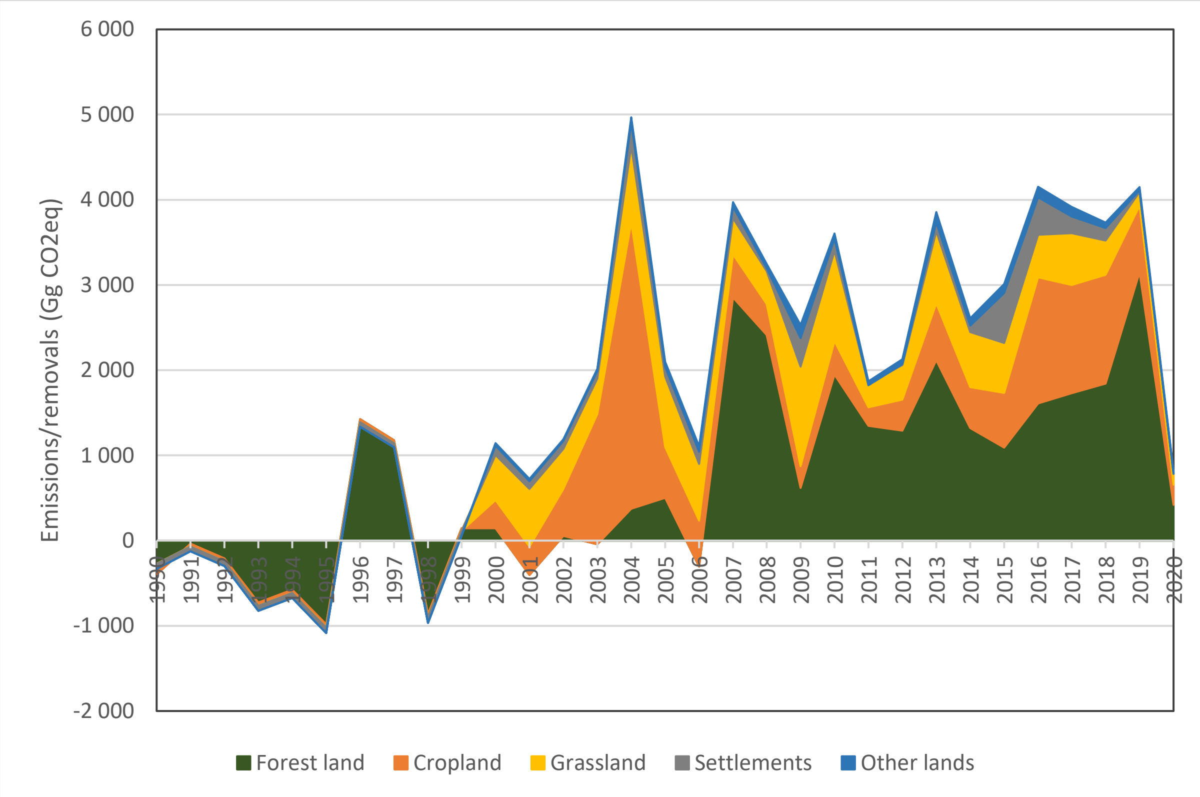
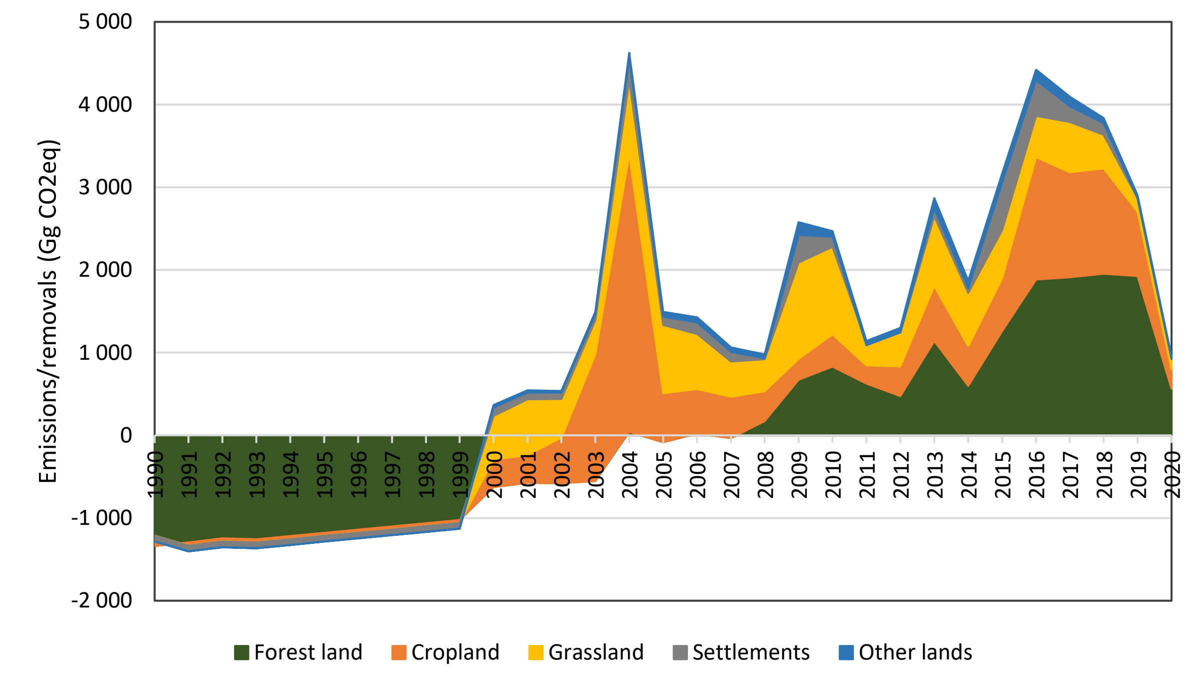


Figure 4: GHG emissions excluding fuelwood removals from the LULUCF sector: 1990-2020.

Biomass burning is also observed to have a significant impact on the GHG emissions for the LULUCF sector. This becomes conspicuous when biomass burning is excluded wherein the trend shows reduced emissions up until the beginning of the 2000s when the sector accelerated as a net source of emissions (Figure 5). When both biomass burning and fuelwood removal are excluded, the trend indicates a net LULUCF sink prior to the year 2000. Biomass burning is prevalent in grasslands and irrigated cropland (sugarcane) and occasionally in forestland, particularly timber plantations.



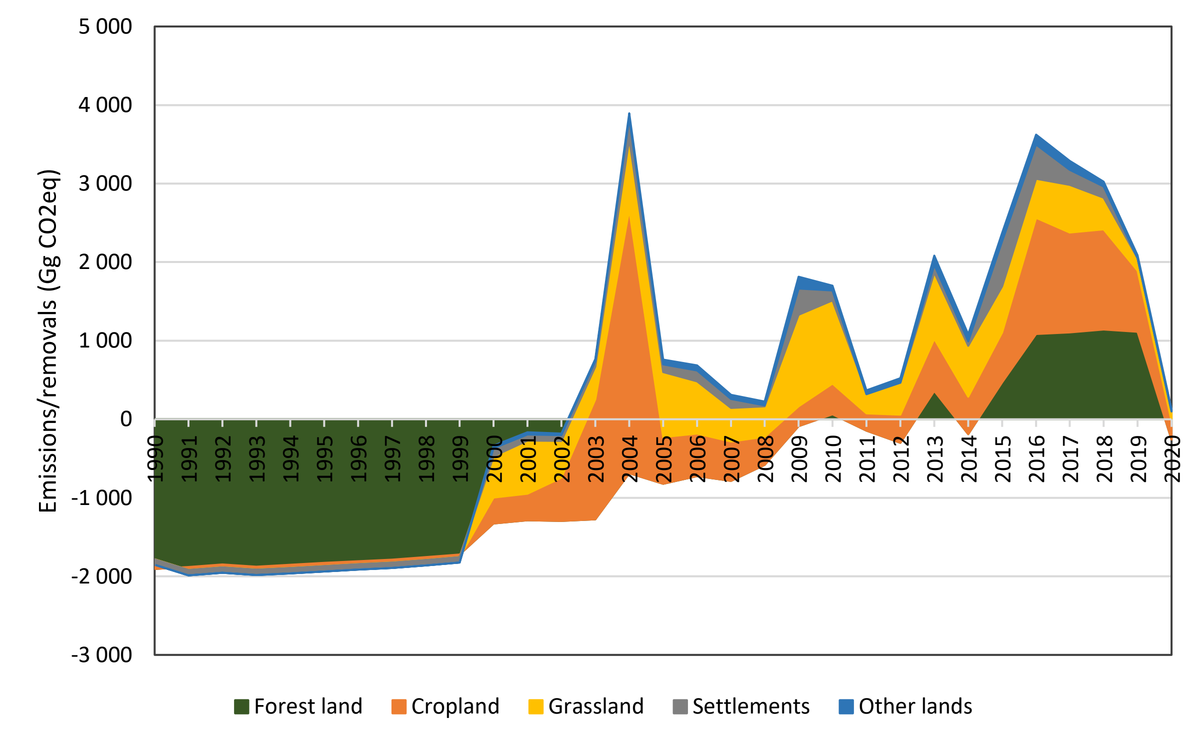


Figure 5: GHG emissions excluding biomass burning (top) and excluding both fuelwood removals and biomass burning (bottom) from the LULUCF sector: 1990-2020.

Compared to the estimates made during the 2018 GHG inventory, the emission estimates from this analysis when including both biomass burning and plantation timber removals (**1,635.28 Gg CO_2e**) are higher where the earlier analysis estimated that **915 Gg CO_2e** was emitted by the Land sector in 2018. However, the results from these two studies are not directly comparable considering that this study has made several changes or improvements in the activity data (including land use categories) as well as the biomass and emission factors resulting in several Tier 2 estimates compared to the previous inventory. The general trends are, however, very similar in that the removals are declining, and emissions are increasing.

4.2.2 Forestland

The Forestland category comprises emissions and removals from forest land remaining forest land and land converted to forest land. Forest land remaining forest land includes both plantation (timber) forests and indigenous (natural) forests comprising of bushlands/thickets, indigenous forests and woodlands). As forementioned, the significant source of emissions from the forestry sector is wood removals from the timber plantations. As demonstrated in Figure 6, the exclusion of the wood removals from the timber plantations results in an overall sink.

Fuelwood consumption and biomass burning in forests (controlled burning and wildfire) are also key sources of emissions. For example, the effect of the 2007/2008 and 2019 wildfires, for instance, can be clearly seen in the time series. These fires adversely affected the forestry industry such that a major timber plantation company, Usutu Forest Products Company (Limited), ceased its operations.

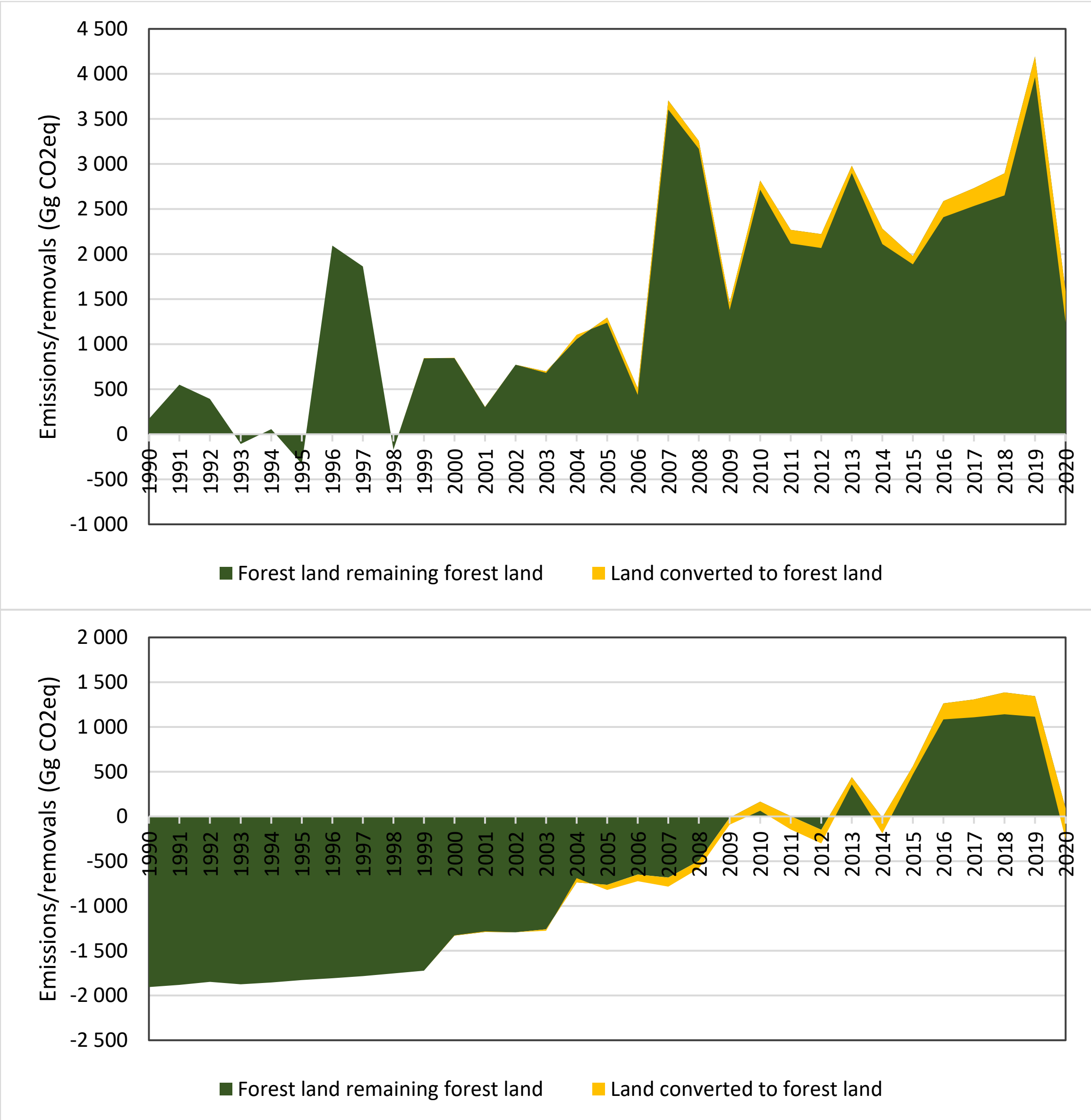


Figure 6: Emissions/removals from the forest land category with (above) and without (below) both biomass burning and fuelwood removals: 1990-2020.

Fire management strategies must, therefore, be enhanced within the timber forests because a single fire event within the timber plantations has significant impacts on the GHG trajectory in addition to other social and economic effects. Similarly, fire management programmes need to be strengthened to reduce unnecessary runaway fires within the indigenous forest ecosystems. The timber plantations must also pay attention to the conservation of natural forests within their estates to avoid emissions resulting from the removal or conversion of carbon-rich montane and riverine forests as well as wetlands. This can be done within the scope of initiatives such as the Forest Stewardship Council (FSC) certification schemes which promote sustainable forest management through environmentally appropriate, socially beneficial and economically viable forest management.

The impact of fuelwood removals highlights the need for energy security in the country. Fuel wood is the major source of energy for the majority of the country's populations, more so in the rural areas. Immense fuel wood extraction from the local indigenous forests has resulted in deterioration of forest structure and increasing emissions as a result. The results imply that increased fuelwood harvest, combined with declining tree density, high population growth and severe climatic conditions, will intensify forest destruction and associated GHG emissions. Thus, policies to reduce the overreliance on fuelwood should focus more on addressing the energy market environment, providing affordable energy alternatives to the majority of the population that is often the larger consumer of fuelwood for cooking and heating.

4.2.3 Cropland

Cropland comprises emissions and removals from cropland remaining cropland and land converted to cropland. The cropland remaining cropland sub-category includes irrigated (predominantly sugarcane) and rainfed cropland (predominantly maize). Emissions from forest conversion and biomass burning of sugarcane are the key sources of emissions particularly from the beginning of the 21st century. The effects of sugarcane cropland expansion as a result of government-driven agricultural projects and expansionist policies, for instance, is notable. The Komati Downstream Development Project (KDDP) and the Lower Usuthu Smallholder Irrigation Projects (LUSIP) are cases in point which led to the rapid expansion of sugarcane plantations during the 2000s and 2010s, respectively. The effects of these initiatives can also be clearly seen in Figure 7. This indicates that in the irrigated sugarcane supply chain, the majority of GHG emissions are generated during land conversion and cane burning during harvesting.

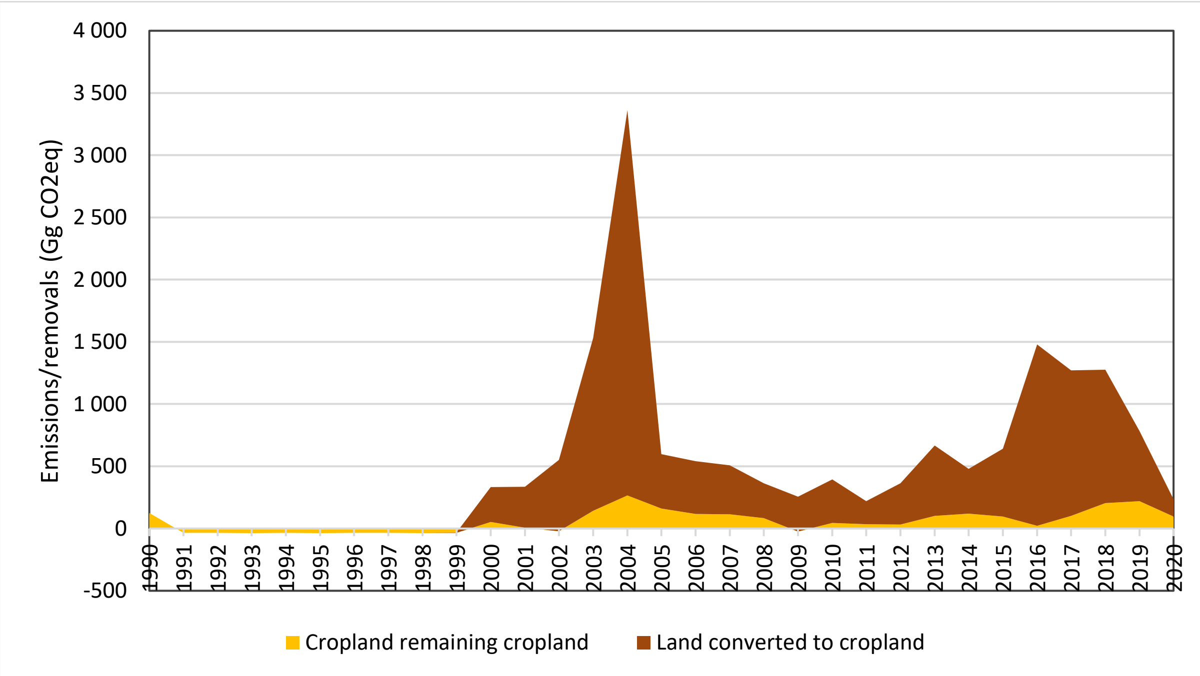


Figure 7: Emissions/removals from the cropland category: 1990-2020.

A low carbon footprint from the sugarcane sector can, therefore, be achieved through minimizing expansion of the sugarcane estate and focusing on intensifying production within currently available land as well as enhancing operational efficiency. The sugarcane sector should also focus on strategies or technologies that aim to, among others, maximise yield and reduce pre-harvest burning which will lead to a reduction in GHG emissions in line with global sustainability trends in the sector.

4.3 Projected trends: 2021 – 2050

The observed baseline trends are projected to result in increasing emissions up to the year 2050 as driven by the aforementioned factors (see also land use change analysis report (Dlamini, 2022) (Figure 8). For instance, sugarcane expansion is expected as the Eswatini government has embarked on the major projects such as the Mkhondvo-Ngwavuma Augmentation Project which is envisaged to involve the construction of large dams, Mpakeni, Ethemba, and Mahamba Gorge dams that are also expected to stimulate the development of new sugarcane plantations and other crops (African Development Bank, 2020). Furthermore, demographic changes are expected to result in an increase in the human population. An increasing rural human population implies additional land for human settlements and subsequently subsistence (rainfed) cropland which will both increase at the expense of indigenous forestland. Whilst the currently illegal cultivation of cannabis is also expected to increase, discussions are also underway to legalise its cultivation in the country. This may also incentivise the clearing of more forestland for this crop for the foreseeable future.

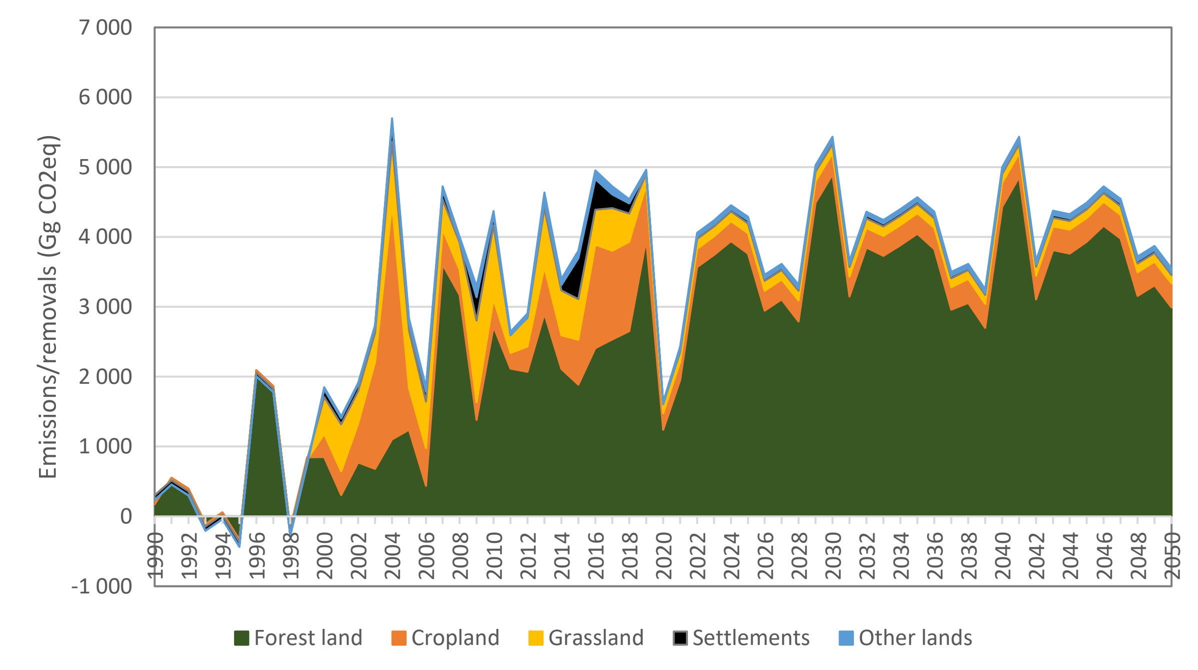


Figure 8: Projected emissions for the LULUCF sector for the period from 2021 to 2050.

The projected trends also affirm the earlier estimates from the 2018 GHG national inventory albeit with differing magnitude of emissions due to the changes in emission factors used. This is also enshrined in the country's Mitigations Assessment Report (Mavimbela et al., 2021) which projected sustained emission within the AFOLU sector until 2030. However, when excluding the fuelwood removals and biomass burning, the sector shows very significant reductions in emissions and a declining sink albeit with interannual variations (Figure 9) which further attests the significance of fuelwood removals and biomass burning in the sector's GHG emissions trajectory. This also points to the ned for interventions in the energy sector aimed at reducing the reliance on fuelwood as well as interventions to minimise runaway forest fires.

Nevertheless, projected emissions from grasslands are expected to decline mainly due to the decline in the area under grassland resulting from human settlement and cropland expansion.

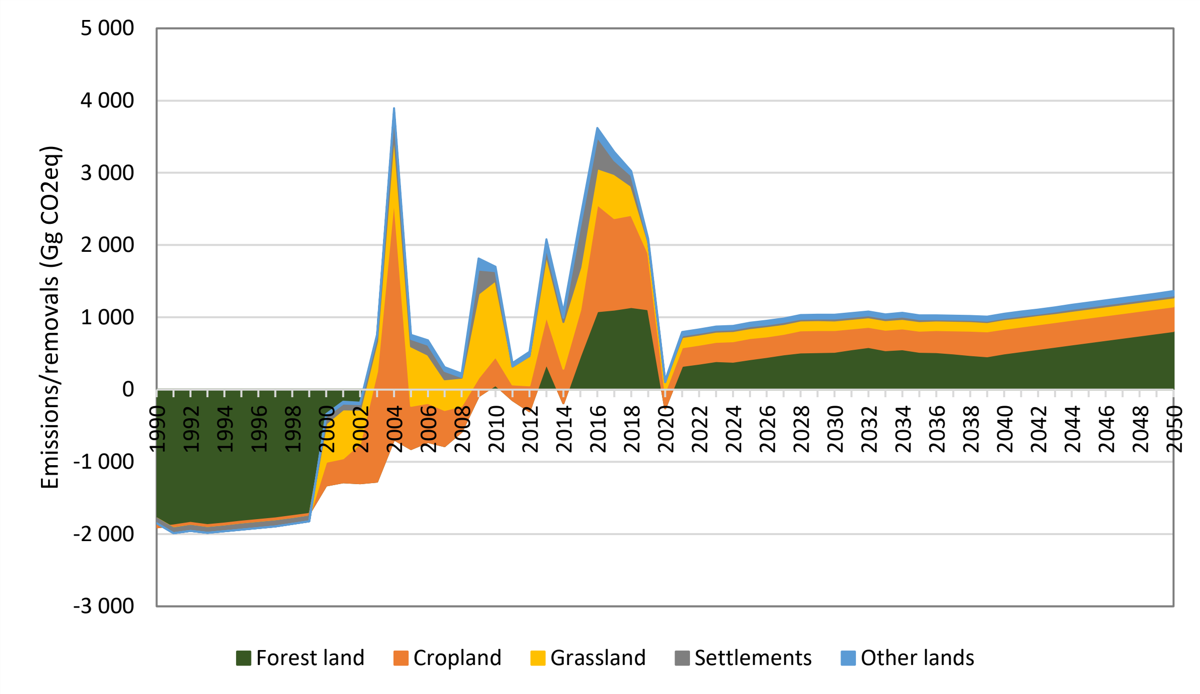


Figure 9: Projected emissions for the LULUCF sector for the period from 2021 to 2050 (without fuelwood removals and biomass burning).

5. SUGGESTED IMPROVEMENTS

The IPCC guidelines encourage continuous improvement of national inventories and based on the findings of this study, the following improvements are proposed:

- This study generated vast amounts of activity data and emission factors that make it possible to perform higher Tier estimations of emissions and removals across the various land uses and carbon pools. This, however, requires intensive analyses that requires more time. Continual and in-depth analysis of this data must therefore be done to improve on the existing estimates. Additional analyses can also be done using existing tools such as the Agriculture and Land Use (ALU) Greenhouse Gas Inventory software which can perform Tier 2 spatially explicit emission and removals estimations for the AFOLU sector along with QA/QC analysis based on the 2006 IPCC Guidelines.

- Disaggregating the indigenous forestland into ecologically meaningful categories such as those used in the 1999 Forest Resource Assessment. On that note, there is an urgent need for the country, through the Department of Forestry, to undertake a field-based forest resource inventory that will not only produce estimates of biomass factors for the different forest types but also the biomass or carbon stocks therein. In addition, detailed surveys on fuelwood consumption should be periodically conducted so as to ascertain the extent of this practice on the country's emissions trajectory. This should also form the basis for a monitoring, reporting and verification (MRV) system for the forestry sector going forward.

- Despite the use of an advanced method for estimating and mapping land use and land use changes in this study, there are opportunities to use other methods to map the land use and land use changes for comparison. One such method is the Landsat-based detection of Trends in Disturbance and Recovery (LandTrendr) which implements continuous series of segments and vertices and may be better suited for areas such as Eswatini where there were limited clear satellite image acquisitions during the earlier periods up to the early 2000s.

- The allocation of land area to land remaining and converted land could be improved. In this study it was assumed that all new conversions occurred from land remaining categories. This is often not the case as a lot of the land being held over for 20 years in the land converted category are being converted before the 20-year period is over. The annual change data developed in this study allows for the tracking of each land parcel which can be used to move away from this assumption and provide a more accurate allocation of land to the land remaining and land converted categories. There was insufficient time to complete this type of assessment due to the large size of the dataset, but this detailed analysis is recommended for improving future inventories.

- Data collection and sharing with the commercial timber and tree crop plantations needs to be strengthened particularly focusing on species-specific annual planted and harvested areas, annual increments and harvested wood products as was done in the past through detailed annual "Commercial Timber Plantations and Wood Products Statistics" that was produced by the Central Statistics Office (CSO). In this regard, a revival of this annual bulletin or development of a data collection tool and mechanism in a similar manner could go a long way in ensuring the availability of high-quality data that can also be used by the timber companies to ascertain their carbon stocks and footprint as required by sustainable development frameworks and key forest product markets.

- Even though data for sugarcane is readily available and well collated, there is a need to improve on providing information on planted sugarcane varieties and cropping practices (e.g. harvesting) undertaken by all the various landowners. Cropland estimates can also be improved by collecting crop-specific area and management information. The modalities and required variables are well covered by the Activity 3 reports. This should also apply to the tree cropland due to the increasing interest in tree crops such as *Macadamia* spp. (F. Muell). Further research on the biomass factors and stock change factors of these different should also be conducted.

- The soil data collected by the Eswatini Water and Agricultural Development Enterprise (ESWADE) through the Land Degradation Surveillance Framework (LDSF) and analysed by World Agroforestry (ICRAF) must be used to produce an updated soil organic carbon stock map of the country. The soil samples collected in various parts of the country are being analysed for chemical and physical properties which also includes soil organic carbon, among others. This will be useful in making below ground carbon stock estimates which are also significant in the country's emissions profile. A system for monitoring of agricultural rangeland health is also being developed using remote sensing based predictive models, allowing for possible tracking of agricultural land and rangeland performance over time.

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