THE ECONOMICS OF
LAND DEGRADATION

Ethiopia Case Study

Soil Degradation and Sustainable Land Management in the Rainfed Agricultural Areas of Ethiopia: An Assessment of the Economic Implications

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Report Main Contributors:
Kaspar Hurni; Gete Zeleke; Menale Kassie; Berhan Tegegne; Tibebu Kassawmar; Ermias Teferi;
Aderajew Moges; Deme Tadesse; Mohamed Ahmed; Yohannes Degu; Zeleke Kebebew; Elias Hodel;
Ahmed Amdihun; Asnake Mekuriaw; Berhanu Debele; Georg Deichert, and Hans Hurni

Editing: Naomi Stewart (UNU-INWEH), and Marlène Thiebault (CDE; for the Executive Summary and Chapter 3)
Reviewers: Dr Berhanu Gebremedhin, Dr Emmanuelle Quillérou

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For further information and feedback please contact:
ELD Secretariat
info@eld-initiative.org
Mark Schauer
c/o Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
Friedrich-Ebert-Allee 36
53113 Bonn, Germany

UNIVERSITÄT
BERN
CDE
CENTRE FOR DEVELOPMENT
AND ENVIRONMENT

WATER & LAND
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CENTRE

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Executive summary

The Economics of Land Degradation (ELD) Initiative is an initiative on the economic benefits of land and land-based ecosystems. The initiative highlights the value of sustainable land management and provides a global approach for analysis of the economics of land degradation. This report summarizes the findings of a case study of the ELD Initiative in Ethiopia. The case study was commissioned by GIZ and carried out by the Centre for Development and Environment (CDE) and the Water and Land Resource Centre (WLRC) from January to July 2014.

Ethiopia is known for its historic agriculture, but also for the associated, widespread, and on-going land degradation. The older agricultural areas of the northeast have long been particularly affected, but the highest soil erosion rates are currently being observed in the western parts of the highlands. The processes of soil erosion and measures to reduce it have been researched extensively in Ethiopia since the 1970s; research activities include long-term monitoring of catchments and experiments of various spatial extents. On this basis of understanding and data availability, Ethiopia offered a unique setting for an ELD case study.

This case study provides a spatially explicit assessment of the extent of land degradation (soil erosion by water) and the costs and benefits of sustainable land management measures. The focus is on areas under rainfed cultivation. The unit of analysis is a pixel of 30 m by 30 m, in line with the resolution of the Landsat imagery used for assessing land cover. The case study area covers 600,000 km^2 or about 54 per cent of Ethiopia's territory, more than 660 million pixels. Of the included pixels, about 239 million were identified as cropland, amounting to about 215,000 km^2 – a surprisingly large area compared to the current statistics that indicate a grain crops area of approximately 123,000 km^2 (CSA 2013a). The dry lowland areas without rainfed cultivation were not considered in the analysis.

The project team worked in small groups, each of which provided unique insights towards an economic valuation of ecosystem services and their importance for the livelihoods of communities. The main focus was on the productive functions of land, as this matters most to small-scale farmers. To provide an economic analysis of these functions, authors looked at different scenarios of sustainable land management implementation over the next 30 years. Other ecosystem functions such as supply of water and sediments to lowland areas and restoration of soils through soil and water conservation as well as off-site impacts of soil erosion were not fully included in the economic analysis. The omission of such ecosystem functions in this analysis, is likely to underestimate the benefits of sustainable land management interventions.

Land cover was mapped using an approach that combined visual delimitation of units of analysis with expert knowledge and automated image classification. This approach made it possible to distinguish cultivated land (i.e., cropland, which in Ethiopia consists of land currently being ploughed or harvested, land with growing crops, land under mixed crop and trees system, and fallow land) from other land use or land cover classes. Unsurprisingly, the actual amount of cultivated land is considerably larger than that indicated by official statistics in use since the mid-1980s, when the rural population was half its current size. The team also mapped large-scale land use systems, inclusive of any foreign direct investments. Results of the study show there has been a considerable expansion and intensification of farming in the past three decades, leading to more soil erosion.

Conservation structure mapping was attempted by an automated procedure of reading linear structures from Google Earth images. However, this approach failed because of the low accuracy of the resulting maps. The team then devised an approximate expert-based modelling approach, built on the assumption of experts that conservation structures existed in about 18 per cent of the country's cropland in 2014, as well as other assumptions about their spatial distribution (e.g., slope and travel time to the cropland from the villages).

Soil erosion and deposition values were estimated using pixel based landscape information and the Unit Stream Power Erosion Deposition (USPED) model, which works with the Universal Soil Loss Equation (USLE) parameters. The USPED model was adapted to Ethiopian conditions based on evidence from the Soil Conservation Research Programme, and calibrated and validated using data from former research stations as well as the Abbay (Blue Nile) Basin. Additionally, some of the USLE parameters were reduced in order to achieve a satisfactory approximation of sediment loss for the Abbay Basin.

These adaptations made it possible to produce a pixel based soil erosion and sediment deposition model for the whole study area and even more importantly, to run different scenarios of investments in the cropland and show their effects after 30 years. However, these scenarios did not consider climate change or changes in the extent of the cropland. Based on net erosion/deposition estimates produced by the USPED model, the present annual net erosion across the study area is –940 million tonnes, or –18 tonnes/ha. This estimate considers currently existing conservation structures, which are present in about 18 per cent of cropland on slopes > 8 per cent in the study area of the USPED model. However, the share of cropland situated on slopes steeper than 8 per cent totals 77 per cent, which means that such area needs soil and water conservation. As a result, conservation structures would need to be built on an additional 59 per cent of cropland (about 12.7 million ha), in order for all sloping cropland to be conserved. Looking exclusively at cropland, the model produced an annual net erosion of –380 million tonnes (–20.2 tonnes/ha). This value could be reduced to –222 million tonnes (–11.8 tonnes/ha) if conservation structures were constructed on all sloping cropland.

The situation is similar in the Grand Ethiopian Renaissance Dam Basin: additional structures in cropland on slopes > 8 per cent could reduce overall net erosion in all land cover classes by 21 per cent, and net erosion in cropland by as much as 43 per cent. In absolute values, this would mean a reduction from –320 million tonnes/yr to –251 million tonnes/yr, a number that could be further reduced when applying conservation measures on all landscapes. However, it should be noted that while the USPED model was calibrated to deliver the ~300 million tonnes of sediment yield estimated for the GERD, it is not exactly known when and how this value was measured or estimated (cf. Abdelsalam 2008).

After modelling soil erosion/deposition for two scenarios (current distribution of conservation structures, and conservation structures on all cropland steeper than 8 per cent), crop production was estimated for a time period of 30 years, based on relationships between production and soil depth. The estimation algorithm was calibrated using information on productivity from reports of the Central Statistical Agency of Ethiopia. The two soil erosion/deposition scenarios assuming different distributions of conservation structures were then augmented with two more scenarios, one assuming the current extent of fertilizer application and the other assuming fertilizer application on all croplands. On this basis, crop production was estimated over the coming 30 years for the four scenarios as:

1. current distribution of conservation structures and currently fertilized croplands;
2. current distribution of conservation structures and fertilizer application on all cropland;
3. conservation structures on all sloping cropland and currently fertilized croplands, and;
4. conservation structures on all sloping cropland and fertilizer application on all cropland.

This analysis showed that Scenario 1 ('business as usual') results in a reduction of crop production by more than 5 per cent over 30 years. The other three scenarios show a crop production similar to current values (Scenario 3) or an increase of about 3 per cent (Scenario 2) and about 10 per cent (Scenario 4). Even if these increases seem moderate, the modelling exercise indicates that crop production can be maintained or slightly increased by applying sustainable land management practices, whereas crop production decreases if none are applied.

The profitability of each management option was then assessed by performing a cost-benefit analysis. The number of scenarios increased from four to eight by performing two versions of the cost-benefit analysis for each scenario: one assuming plantation of fodder grass on all conservation structures and the other assuming no plantation of fodder grass. Growing fodder grass on the structures increases the productivity of conserved farmland due to the production on the otherwise unused area of the conservation structure. A variety of such management options exist (e.g., growing fruit trees or high-value legumes), but were not considered in the study due to lack of data. The authors believe that including such management options in the analysis upon data availability is likely to increase the benefits of conservation structures. For each of the eight scenarios, respective costs and benefits were defined and the cost-benefit analysis was performed at pixel level for the 30 years, assuming a discount rate of 12.5 per cent. To compare the scenarios and determine the most profitable management option or combinations of options for a given area, net present value was calculated for each scenario at pixel level and summarised by administrative unit.

Comparison of the different scenarios' net present values at wereda level showed that soil and water conservation measures combined with fertilizer application and fodder grass generally have a positive net present value suggesting investment in sustainable land management is profitable, all else being equal. However, there are regional differences: in Tigray, for example, a large number of conservation structures have already been built; accordingly, the net present value can be increased only by additionally planting fodder grass on the conservation structures. In areas where soils are shallow, i.e., some parts of the Amhara Region, building conservation structures and planting fodder grass on them is profitable, whereas fertilizer application has a limited effect due to shallow soils and thus cannot increase production enough to compensate for fertilizer costs. Across most of the Oromia, Benishangul-Gumuz, and Southern Nations, Nationalities, and Peoples' (SNNP) regions, the full range of management options that include conservation structures, fertilizer application, and fodder grass, is the most profitable scenario.

In addition to comparing scenarios, the relationship between the current soil erosion rate and the net present value of the best management option for each area was also examined. This information is useful for planning development interventions to reduce soil erosion: for example, with the best management option, areas with a high erosion rate and a low net present value are likely to need more support than areas with a low erosion rate and a high net present value. Spatial differentiation is thus key in prioritizing development interventions and implementation. The ELD Ethiopia Case Study database provides an excellent source of data for such differentiation.

Abbreviations and Amharic terms

Berha	Desert belt (very hot and arid)
CBA	Cost-benefit analysis
CDE	Centre for Development and Environment, University of Bern
CSA	Central Statistical Authority of Ethiopia
DAP	Di-Ammonium Phosphate, fertilizer
Dega	Highland belt (cool, humid)
DEM	Digital Elevation Model
ELD	Economics of Land Degradation
ETB	Ethiopian Birr
EUR	Euros
FAO/LUPRD	Food and Agriculture Organization
GERD	Grand Ethiopian Renaissance Dam
GIS	Geographic Information System
HICU	Homogenous Image Classification Unit
Inset	False banana
Kebele	Community below wereda
Kolla	Lowland (semi-arid to sub-humid hot) belt
LULC	Land Use and Land Cover
N	Nitrogen (in soil)
NPV	Net Present Value
P	Phosphorus (in soil)
Region	National state (below federal state), with governmental status
RUSLE	Revised Universal Soil Loss Equation (model)
SCRP	Soil Conservation Research Programme
SLM	Sustainable Land Management
SNNP	Southern Nations, Nationalities and Peoples' (Region)
SWC	Soil and Water Conservation
Tef	Eragrostis tef (a major crop endemic to Ethiopia)
Urea	Urea or carbamide, nitrogen-release fertilizer
USLE	Universal Soil Loss Equation (model)
USPED	Unit Stream Power Erosion Deposition (model)
Wereda	District, administrative unit between zone and kebele
Weyna Dega	Middle altitude warm and humid belt (optimum for agriculture)
WLRC	Water and Land Resource Centre, Addis Abeba
Wurch	Frost belt (cold)
Zone	Administrative unit between region and wereda

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Important Note:

When analysing the costs and benefits of sustainable land management options for the rainfed agricultural area of Ethiopia the authors considered physical, biological and agronomic soil and water conservation measures. Physical measures included structures on cropland to be aligned along the contour, such as level or graded bunds, but no waterways or cutoff drains were considered. Biological measures included grasses on such structures, but no fruit trees along them, nor high-value shrubs such as *Gesho* or legumes such as *Pigeon pea*. Agronomic soil and water conservation measures included fertilizer on cropland, but no minimum tillage, compost or mulching. Authors are aware that the net present value of investments could have been even better if such management options were also included. They, however, considered the ones selected as 'must haves', and the others as 'nice-to-haves', which could be built into the framework fairly easily once economic data becomes available for them as well.

In this report the term 'economic' refers to financial valuation, i.e. authors performed a financial cost-benefit analysis to measure the profitability of sustainable land management options to smallholder farmers in Ethiopia. The study focused on a cost-benefit analysis from an individual farmer's perspective and aggregated the results in an up-scaling approach. It thus assessed costs and benefits related to on-site impacts of soil erosion and deposition in rainfed agricultural areas, but it did not include off-site impacts, e.g., damage to infrastructure such as roads, bridges and buildings, irrigation canals, water supply systems, or siltation of dams. The established framework nevertheless allows the integration of such information upon data availability.

On a more technical level, the report contains quantitative statements about soil erosion and deposition of eroded soil material downslope. In order to differentiate between the two, negative values are often used for soil erosion, e.g., –22 tonnes per unit area, and positive values for soil deposition, e.g., (+)15 tonnes per unit area. Statements on soil erosion or deposition may cover whole watersheds, with quantities of sediment loss reaching amounts such as –380,000,000 tonnes/yr. Authors were not entirely consistent in the use of negative values, however, soil loss may be referred to by positive values where there is no need to distinguish between erosion and deposition.

Finally, some of the parameters in the framework for the economic analysis of sustainable land management practices had to be modelled. Due to limited data availability, authors opted for an expert-based modelling approach, which combined expert knowledge with available empirical evidence. Limitations related to these parameters are described in the report and should be considered when interpreting results.

Administrative boundaries as shown in the maps and figures are not authoritative.

CHAPTER

01 Background

1.1 The ELD Initiative

The Economics of Land Degradation (ELD) Initiative focuses on land degradation and sustainable land management (SLM) in an economic context at the global level. This includes the development of approaches and methodologies for total economic valuation that can be applied at local as well as at global level (ELD Initiative 2013). The goal of the ELD Initiative is to make economics of land degradation an integral part of policy strategies and decision-making by increasing the political and public awareness about the costs and benefits of land and land-based ecosystems (ELD Initiative 2014).

Specifically, the ELD seeks to look at livelihood options within and outside of agriculture, to establish a global approach for the analysis of economics of land degradation, and to translate economic, social, and ecological knowledge into topical information and tools to support improved policy-making and practices in land management suitable for policy makers, scientific communities, local administrators and practitioners, and the private sector. This enables informed decisions towards strengthening sustainable rural development and ensuring global food security (ELD Initiative 2014).

1.2 Land and soil degradation in the Ethiopian Highlands

The rainfed agricultural areas of Ethiopia (almost a synonym for the Ethiopian Highlands) are a paradigmatic example for doing an ELD Case Study. The highlands are favourable for rainfed agricultural activities, a main source of livelihood for about 87 per cent of Ethiopia's population (94 million in 2014) and around 75 per cent of the country's live-

A typical Ethiopian landscape with little soil and water conservation in western Borena (Wello) stock (60 million units in 1990) (Hurni 1993; Shiferaw & Holden 1998; Asrat et al. 2004). However, land degradation in this area is considered to be one of the severest cases worldwide (Nyssen et al. 2004). The degree and extent of past and current rates of deforestation and degradation continue to increasingly threaten the food security of the rural poor, with (yet unknown) implications on the national economy (Demeke 2002).

Soil erosion by water is the dominant degradation process and occurs particularly on cropland, with annual soil loss rates on average of 42 tonnes/ha for croplands, and up to 300 tonnes/ha in extreme cases (Hurni 1993). Other degradation processes include intensified runoff from grasslands and related gullying, as well as high soil erosion rates from badlands (heavily degraded lands). The practices of the small-scale farmers are the main 'cause' of these processes, although in recent decades they have started taking action alongside government initiatives.

1.3 Contribution to the goals of the ELD Initiative

Spatially explicit information on the degree and extent of both soil degradation processes and investments in SLM technologies in the rainfed agricultural areas of Ethiopia is not yet available. Since such information is crucial for informed decision-making (Pinto-Correia et al. 2006), the ELD Ethiopia Case Study aims to contribute to filling this gap. It focuses on the development of a framework for a spatially explicit assessment of land degradation (soil erosion by water) and analysis of the costs and benefits of SLM practices. By displaying spatial differences on the status and current processes of land and soil degradation, on implemented and planned SLM technologies and related costs and benefits, potential adaptions of SLM technologies and livelihood options outside of agriculture can be economically valued. In this way, the ELD Ethiopia Case Study contributes to the goal of the ELD Initiative of supporting informed decision-making.

In terms of ecosystem services, the proposed assessment primarily addresses the productive functions of land and water, particularly through the cultivation of cereals, pulses, and other crops in the ox-plough systems of the rainfed agricultural areas, which enable a subsistence-based livelihood for a great majority of the Ethiopian peoples. The focus on cropland is justified in view of its importance as a primary cause of soil erosion and degradation. It is further justified due to its considerable share of land cover (about one third of the highland area), and the direct dependence of farming systems on what the soil is able to produce. Grassland is also a major land cover class (for animal feed), which has been included in the land cover component, but is not analysed further in the economic assessment, as soil erosion on grassland is only a fraction of the amount of erosion from cropland when compared on a per unit area basis.

Other ecosystem services like biodiversity, amenity function, or other provisioning services such as water delivery to downstream areas, are not economically valued here any further. However, for the latter case, the soil erosion and sediment deposition analysis will allow for a detailed assessment of potential sediment delivery rates in any river system originating from the highlands, although their accuracy is based on very little calibration information used here. Furthermore, other ecosystem services can be analysed in the future based on the detailed land cover analysis attempted here.

1.4 Location and scope

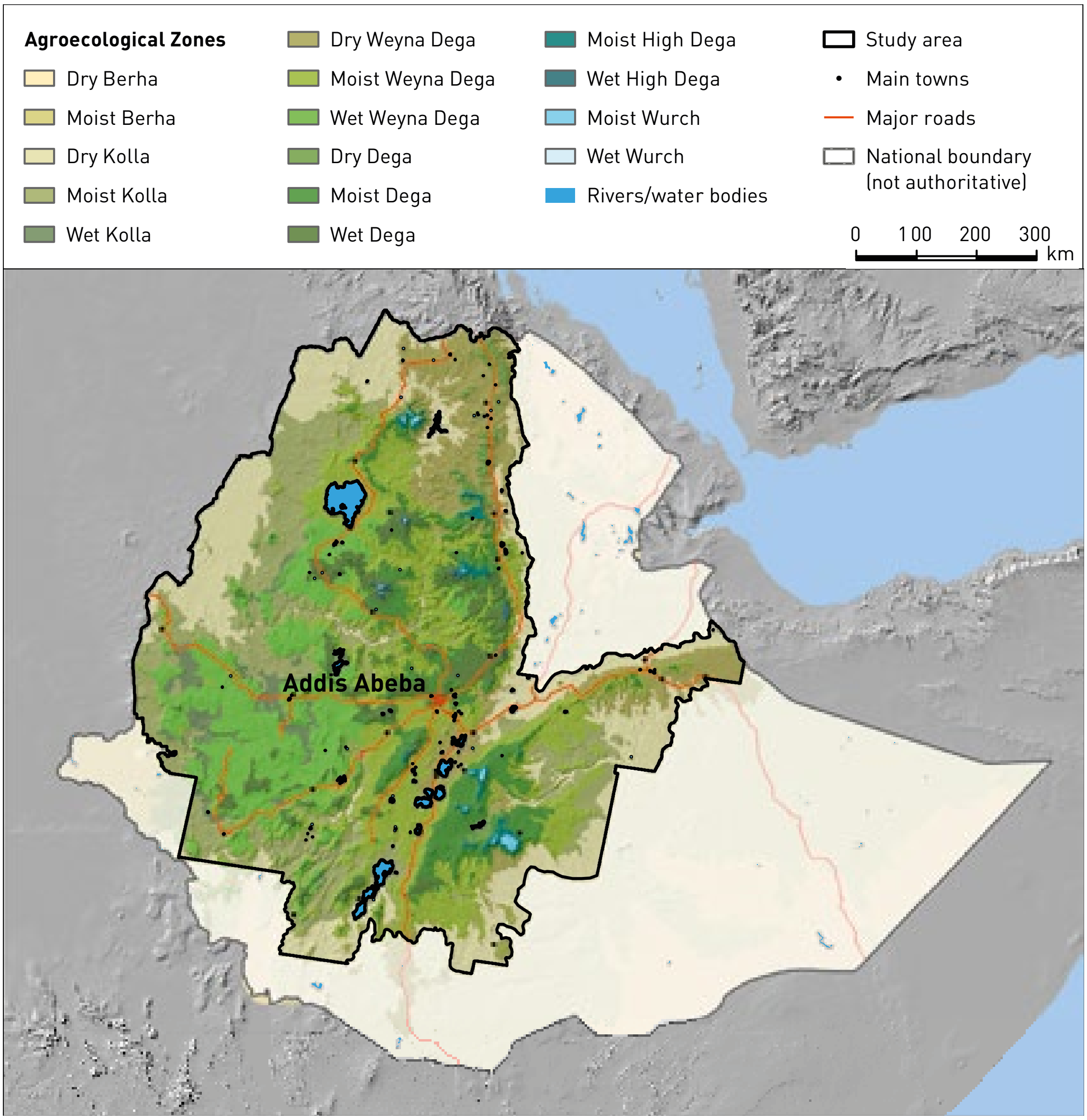
This study focuses on the parts of Ethiopia where rainfed agriculture is practiced, which covers almost 600,000 km^2 = 54 per cent of the country, and 84 per cent of the land is 1000 m/asl and above. Lowland areas below 1000 m/asl were only analysed if they showed rainfed agriculture, although most of it is semi-arid to arid and used mainly by pastoralists who do not normally practice it. As a result, these areas were not analysed in this case study as they are much less affected by human-induced soil degradation than the small-scale farmers in the moist to wet highlands.

The scope of this study is to thus:

(a) Produce a high-resolution land cover map (pixel size: 30 m x 30 m, or 900 m^2 per pixel) using 30 land cover classes (*Table 2* and *Figure 4*), from forest to grassland, cropland to settlement, and bare land to water body, covering over 660 million pixels for the case study area (599,864 km^2);

FIGURE 1

Extent of the ELD Ethiopia Case Study, including nearly 100 per cent of the rainfed agricultural area in Ethiopia



Agro-ecological zones follow Ethiopian terms, *Berha* being desert lowlands, *Kolla* being semi-arid lowlands, *Weyna Dega* being ecologically favourable humid middle altitudes, *Dega* and high *Dega* being coldish to cold highlands, and *Wurch* being cold alpine meadows (Hurni 1998)

(b) Model the occurrence of soil and water conservation structures and fertilizer application on cropland in the study area;

(c) Creation of a pixel based database including the information required to model soil erosion/deposition, to estimate crop production, and to perform a cost-benefit analysis (CBA) of different management options;

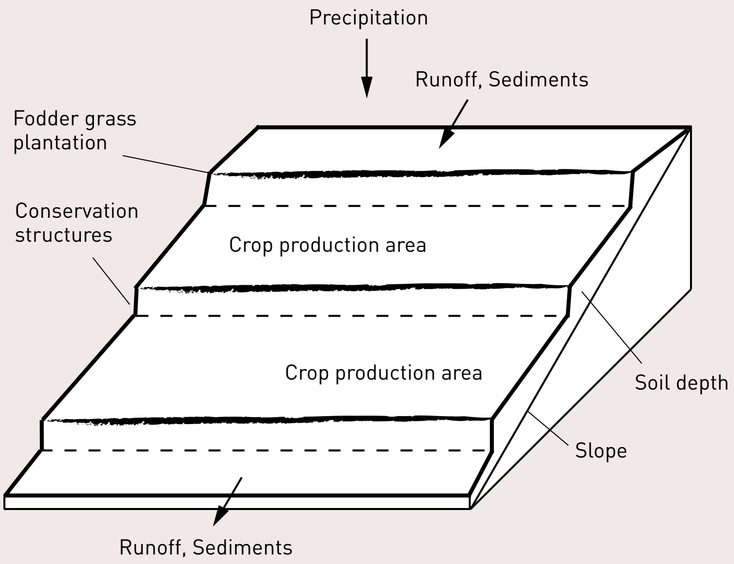
(d) Model soil erosion/deposition using calibration and validation data from research catchments (SCRP 2000) as well as the Abbay (Blue Nile) River Basin;

(e) Estimation of crop production from the soil depth for the current situation ('business as usual') and for the coming 30 years assuming different management options, and;

(f) Compute a CBA of the current situation ('business as usual') and of seven additional scenarios over 30 years, from 'business as usual' to 'enhanced SLM', to reduce soil erosion and

FIGURE 2

Example of a conserved cropland pixel (30 m x 30 m) and some of the parameters used for the CBA



enhance productivity without agronomic improvements.

For each rainfed cropland pixel, the parameters shown in *Figure 2* were considered.

In the study area, there are about 239 million such cropland pixels. About 31 million of these pixels were later on defined by the digital elevation model (DEM) as riverbeds. These pixels were excluded from the analysis because the soil erosion/deposition model would give exorbitant results beyond plausibility. What remained as rainfed agricultural areas of Ethiopia were 208 million cropland pixels for which eight scenarios were modelled, described as follows (also see *Table 1* for a systemic overview):

Scenario 1.1: Business as usual, i.e., current distribution of conservation structures (fanya juu bunds, soil bunds, and stone terraces) and currently fertilized croplands, the latter on unconserved flat crop lands as well as on conserved sloping cropland

Scenario 1.2: Business as usual, and planting agro-ecological suitable fodder grasses on current conservation structures

Scenario 2.1: Current distribution of conservation structures with fertilizer use on all rainfed croplands

Scenario 2.2: Current distribution of conservation structures with fertilizer use on all rainfed croplands, and planting agro-ecological suitable fodder grasses on current conservation structures

Scenario 3.1: Conservation structures on all rainfed croplands with slopes of more than 8 per cent gradients, and current distribution of fertilizer use on flat lands as well as on currently conserved croplands

Scenario 3.2: Conservation structures on all rainfed croplands with slopes of more than 8 per cent gradients, and current distribution of fertilizer use on flat lands as well as on currently conserved croplands, and planting agro-ecological suitable fodder grasses on all conservation structures

Scenario 4.1: Conservation structures on all rainfed cropland with slopes of more than 8 per cent gradients and fertilizer use on all croplands

TABLE 1

Systematic overview of scenarios on rainfed croplands in Ethiopia

Scenario	Current conservation structures on cropland	Conservation structures on all cropland	Currently fertilized croplands	Fertilizer on all cropland	Grasses on current conservation structures	Grasses on all conservation structures
1.1	×		×			
1.2	×		×		×	
2.1	×			×		
2.2	×			×	×	
3.1		×	×			
3.2		×	×			×
4.1		×		×		
4.2		×		×		×

Scenario 4.2: Conservation structures on all rainfed cropland with slopes of more than 8 per cent gradients, fertilizer use on all croplands, and planting agro-ecological suitable fodder grasses on all conservation structures

1.5 Framework

Figure 3 presents an overview of the framework used for this study, including the six steps to estimate the benefits and costs of action (1–6) and one to take action (7), as outlined in the ELD Interim Report (ELD Initiative 2013). These steps are:

1. Inception;
2. Geographical characteristics;
3. Types of ecosystem services;
4. Role of ecosystem services and economic valuation
5. Patterns and pressure;
6. Cost-benefit analysis and decision-making, and;
7. Take action.

Steps 3 and 4 of the approach as described in the ELD Interim Report are not displayed in *Figure 3*, as they were defined a priori by limiting the analysis to the productive functions of land and water in the rainfed agricultural areas of Ethiopia (ELD Initiative 2013). The analysis shown in the framework is pixel based at a 'national' level, at least for the rainfed agricultural areas. It also provides information at local levels, i.e., from pixels to farming communities and all administrative units governing them, as well as for any watershed delineation that may be required for watershed management planning.

For this framework, authors looked at the creation of land cover data and the detection of physical soil and water conservation (SWC) structures from remote sensing, both of which are required for the spatial assessment of soil erosion/deposition. Knowing these, and the status and annual rates of soil degradation (erosion/deposition), agro-ecology, cropland areas, and a number of other related factors, respective crop production could then be estimated for 30 years, which will be used for the economic valuation of various measures (and combinations thereof) to reduce soil erosion. Such spatial information then provided the basis for recommendations on appropriate SLM technologies, and the related costs and benefits within a 30-year perspective. Based on this last step, a synthesis and discussion of livelihood options within and outside agriculture was performed wich could improve policy decision-making.

This framework provides a first approach to implement a spatially explicit (pixel based) CBA of land degradation/soil erosion and different management options at 'national' level. There is ample room for improvement, particularly by updating any of the layers upon the availability of more detailed information. The case study has two major weaknesses that should be taken into account when interpreting the results:

- The distribution of current soil conservation structures is based on expert knowledge about current efforts invested by regions since the 1970s, improved by some modelling of their most likely distribution using proximity to settlements and roads, steepness of terrain, and cropland (the study's initial approach using remote sensing information for detecting such structures automatically had failed).

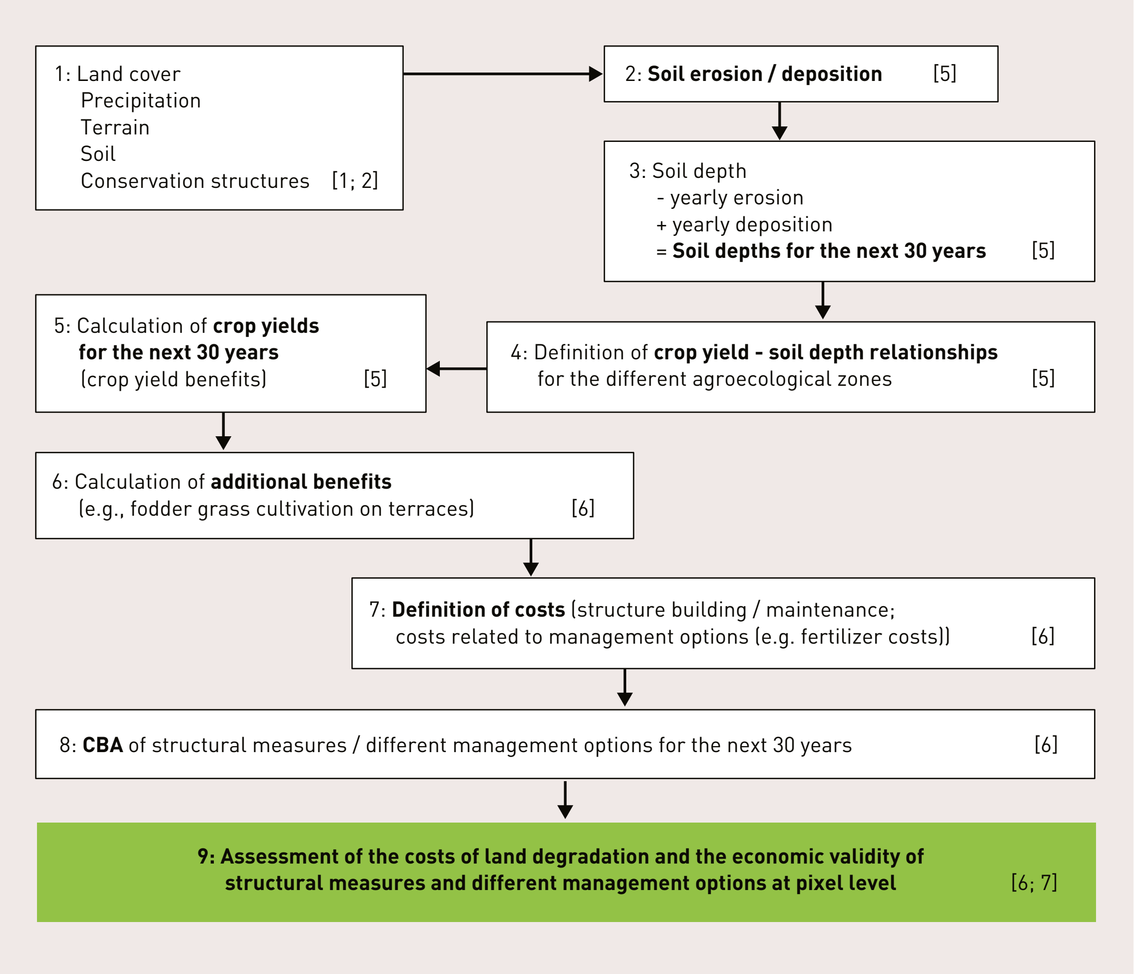
- The erosion/deposition model could be calibrated and validated for small catchments for which long-term data existed, such as in the Soil Conservation Research Programme (SCRP) research catchments. However, the application of the model to larger basins had to be done using just one piece of information from the Abbay (Blue Nile) Basin that may date as far back as 50 years, namely an annual sediment delivery of at least 300 million tonnes for a major part of the basin (Abdelsalam 2008).

In general, however, authors are very pleased with the outcomes of this study, which can be adapted (if more detailed information becomes available) to small areas, such as catchments from a few hectares to square kilometres in seize, but also to other regions world-wide for which similar conditions exist.

The following chapter presents the methodological components required for the implementation of this framework.

FIGURE 3

Framework for the assessment and economic valuation of soil degradation and various SLM practices in the rainfed agricultural area of Ethiopia and related ELD step
(1 to 9 are steps in the assessment; [1] to [7] refer to the ELD Initiative [see text]).



CHAPTER

02

Components of the ELD Ethiopia Case Study

A series of base layers need to be created in order to model soil erosion/deposition and to perform a CBA of different agricultural management options. Authors used remote sensing (e.g., land cover data) and quite often also GIS modelling (e.g., for approximating the distribution of the currently existing conservation structures, application of fertilizer, or crop prices). This helped in translating the expert knowledge and statistical data into spatial information. The methodologies, approaches, assumptions used to create these base layers, and main results from each component are presented in the following chapters.

2.1 Component 1: Land cover mapping

2.1.1 Background and scope

For this study, up-to-date and detailed land cover information at a 30 m pixel resolution was required. Such information is available in terms of resolution and detail, but only at local case study scales scattered over the Ethiopian Highlands. Only a few datasets exist at the national scale, namely those produced by the Ethiopian Highlands Reclamation Study in the 1980s, the Woody Biomass Inventory and Strategic Planning Project in the 1990s, and a land use land cover (LULC) map developed by FAO/LUPRD in the 1980s. However, these are all outdated and did not show sufficient detail for this study. In order to assess the economics of land degradation, this study required land cover data at a scale that represents the local level land cover characteristics while still covering the rainfed agricultural areas of Ethiopia. Consequently, authors needed to produce a land cover dataset to suit these requirements.

A major challenge in mapping land cover from remote sensing imagery in Ethiopia was the complex biophysical and socio-cultural setting. The long history of smallholder cultivation in many parts of the highlands has resulted in a heterogeneous landscape consisting of a mix of small patches of land cover classes. These land cover mosaics also vary in terms of composition and frequency of occurrence in the wider landscape. There is also heterogeneity in terms of land cover classes and their composition between the agro-ecological zones, related to varying cultural practices, farming systems, precipitation regimes, and last but not least, the often rugged terrain.

There are additional challenges related to the acquisition dates and spectral and spatial resolution of remotely sensed imagery. Firstly, the rugged terrain heavily affects the spectral reflectance captured by satellites (Dorren et al. 2003). Depending on the gradient of the slope, the same land cover can appear completely different in the remote sensing imagery and can be easily confused with other land cover classes. Secondly, the acquisition dates of images with low or no cloud cover are mostly during the dry season, but during this time remote sensing specialists are confronted with the problem of land cover (e.g., grasslands and croplands) having very similar spectral reflectance, which is also easily confused.

As a result, commonly applied remote sensing classification approaches (e.g., supervised classification of a whole image after the collection of few training and verification areas) do not allow for an accurate classification and often under- or overestimate certain land cover features. To derive a land cover dataset that accurately represents the heterogeneity of the Ethiopian landscape, contextual approaches were required that considered the complex biophysical and socio-cultural setting so that the local settings could be properly captured.

2.1.2 Data and methodology

The following sections describe the remote sensing data used to derive land cover, selection of land cover classes, and the development of classification approaches and methodologies.

Remote sensing imagery

In terms of image availability and aspired spatial resolution for this study, Landsat data (30 m pixels) was found to be appropriate. With this data, the final map can be considered reliable for scales between 1:50,000 and 1:100,000. Considering the long time-series of Landsat data, as well as the continuation of the Landsat mission (Landsat 8 was launched in spring 2013), an approach developed with Landsat data allows for a repetition of the land cover mapping targeting different time steps, also in the future. Additionally, Landsat images are provided for free (e.g., earthexplorer.usgs.gov). In this study, Landsat Thematic Mapper data covering the period from 2008–2011 was used. Due to cloud and haze cover, it was not possible to use images from only one specific year.

Selection of land cover classes

The Landsat images chosen for the classification were thoroughly assessed in order to identify the features that could be reasonably mapped and extracted from the imagery. Authors assumed that the appropriate mapping detail should at least involve features showing a 150 m x 150 m extent. Based on this, and considering the objectives of the study, a classification scheme involving 30 distinct land cover classes was then defined.

Approach and methodology

In order to deal with the complexity and heterogeneity of the land cover, the following approach was applied to obtain a dataset that covers the whole study area while still capturing the local characteristics of the complex Ethiopian rainfed agricultural landscape:

- Deriving Homogenous Image Classification Units (HICUs) that subdivided each Landsat image into smaller units where similar land cover mosaics occur was found to be a suitable classification approach. HICU development was done using multiple information sources such as altitude, terrain, farming system, rainfall pattern, and soil. This approach resulted in a varying amount of HICUs within a Landsat image, depending on the location and landscapes. In areas with relatively less heterogeneity, e.g., in flat highland plateaux like Central Gojam, Central Oromia, Gambela, and Benishangul-Gumuz regions, 20–30 HICUs per Landsat image where sufficient. In more heterogeneous landscapes, e.g., the northern mountainous areas like Wello, Gonder and Tigray, up to 100–200 HICUs per Landsat image were delineated.
- The next step of the LULC mapping consisted of identifying the dominant and subordinate land cover features for each HICU, hereto after referred as majority and minority classes. For each HICU this involved grouping land features into minority and majority classes based on the occurrence, dominance, and distribution of the land features. While the classes varied for each HICU, they usually included forests (church forests, plantation forests, protected high forests), homestead plantations, irrigated landscapes, large-scale investments, settlements, and ponds and small lakes. Depending on the location of the HICU in the study area, forests could be either a majority class (covering a large share of the HICU) or a minority class, while the other aforementioned land features usually were a minority class (covering small areas, scattered within the HICU). Different approaches like manual digitizing, edge enhancement, and NDVI thresholding were used to extract the majority and/or minority classes from the imagery. The extracted classes were combined and areas of their occurrence masked within each Landsat image, so that they would not distort the further classification process.
- For each HICU, an unsupervised classification was run (ISODATA cluster algorithm) and 20–40 unsupervised classes generated. These classes were then checked against high resolution Google Earth imagery and labelled by experts with experience in the areas where the images where located. In case the unsupervised classification within a HICU did not provide sufficiently detailed classes, the amount of unsupervised classes was increased, and if the classification was still not satisfactory, the HICU was further subdivided.
- Merging of the HICUs and the Landsat images, and crosschecking of assigned classes was done in a mutual effort by experts. This was necessary, as for example, at some of the image boundaries, differences in the attributed land cover classes could be observed. These areas

were relabelled after coming to a consensus among the land cover experts.

This analysis resulted in a highly detailed land cover dataset for the extent of the rainfed agricultural areas of Ethiopia. Results, including spatial statistics and maps, are presented in the following section.

2.1.3 Results of the land cover mapping

The creation of a Landsat-based land cover dataset in five months (given the short project time of only seven months) was a huge task and an accomplishment itself. The LULC mapping covers 613,957 km^2 of rainfed agricultural landscape in Ethiopia

FIGURE 4

Land cover classes of the study area

(Tibebu Kassawmar et al., in submission)

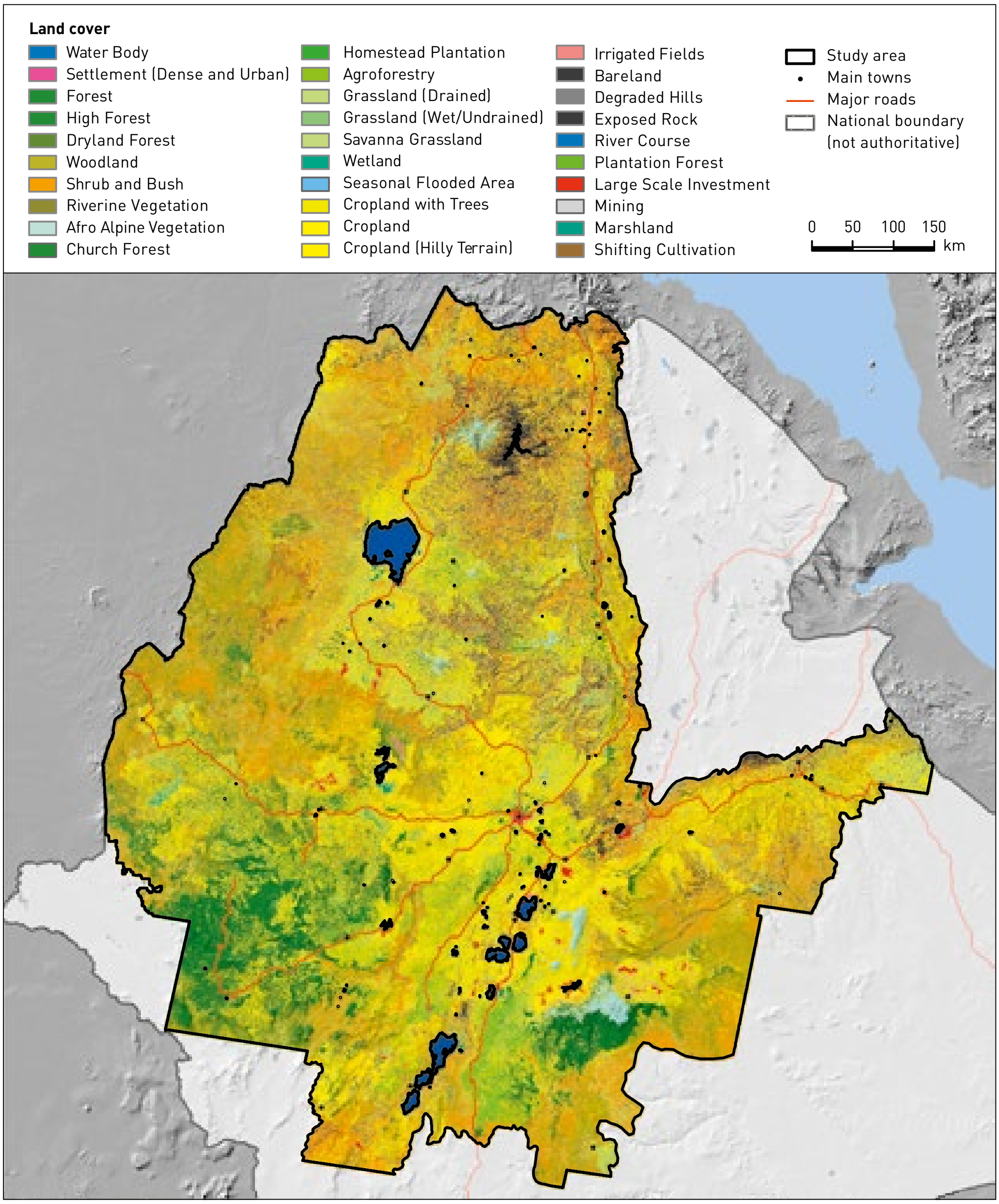


TABLE 2

Summary of LULC class statistics for the rainfed agricultural area of Ethiopia (2010)
(Note that 100% is the case study area, ~54% of Ethiopia)

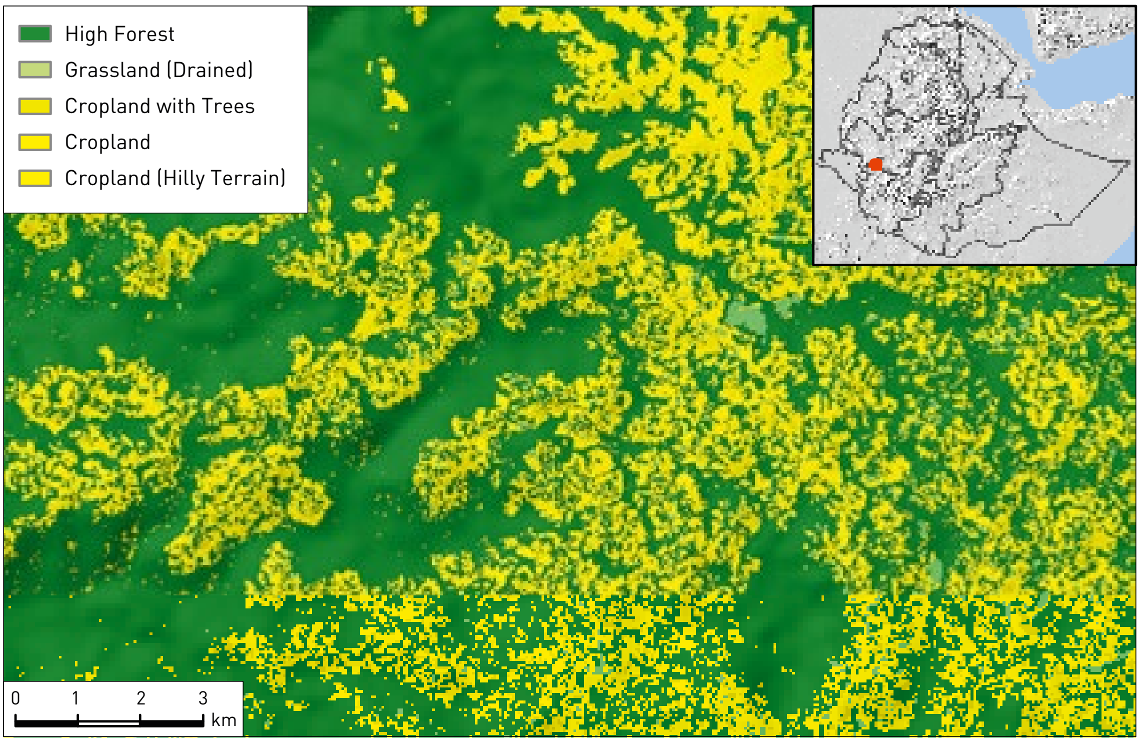
Major classification	Sub-classification	Detailed classification	Area (km^2)	(%)
Woody vegetation types	Forest	High forest	46,568	7.58
		Mixed forest	5,623	0.92
		Plantation forest	2,643	0.43
		Dryland forest	4,078	0.66
		Church forest	44	0.01
		Homestead plantation	3,507	0.57
		Riverine forest	1,688	0.27
	Woodland types	Dense	57,504	9.37
		Open	27,629	4.50
	Shrub and bush types	Dense	48,642	7.92
		Open	86,428	14.08
	Total		**284,354**	**46.31**
Cropland types	Cropland without trees		165,124	26.89
	Cropland with trees		44,462	7.24
	Cropland on hilly terrain		4,514	0.74
	Shifting cultivation		2,807	0.46
	Large scale investments		1,803	0.29
	Total		**218,709**	**35.62**
Grassland types	Drained grassland		51,284	8.35
	Less drained grassland		7,101	1.16
	Savanna grass		100	0.02
	Total		**58,485**	**9.53**
Wetland types	Marsh and swamps		919	0.15
	Water bodies		6,550	1.07
	Total		**7,469**	**1.22**
Agroforestry			13,444	2.19
Irrigated fields			351	0.06
Bare lands			13,098	2.13
Degraded hills			10,482	1.71
Exposed rock			2,424	0.39
River course			731	0.12
Afro-alpine vegetation			2,483	0.40
Settlements			1,881	0.31

around the year 2010 (with some data from 2009/2011) for the year 2010. The information that can be extracted from this dataset is enormous, making it a multi-purpose dataset that can fit wide ranges of data requirements. With the categories representing detailed surface vegetation conditions, it is especially well suited for land degradation and erosion modelling, as performed in this study. Additionally, the detail of the data allows the extraction of land cover statistics with a level of

Examples of church forest (top), dense shrub and bush (lower left), and open shrub and bush (lower right)

FIGURE 5

High forest dominated landscape (the Illu Ababora zone in Oromia region)



accuracy that was not previously available. Some of the statistical findings and highlights related to the land cover data are provided further on.

The woody vegetation landscapes

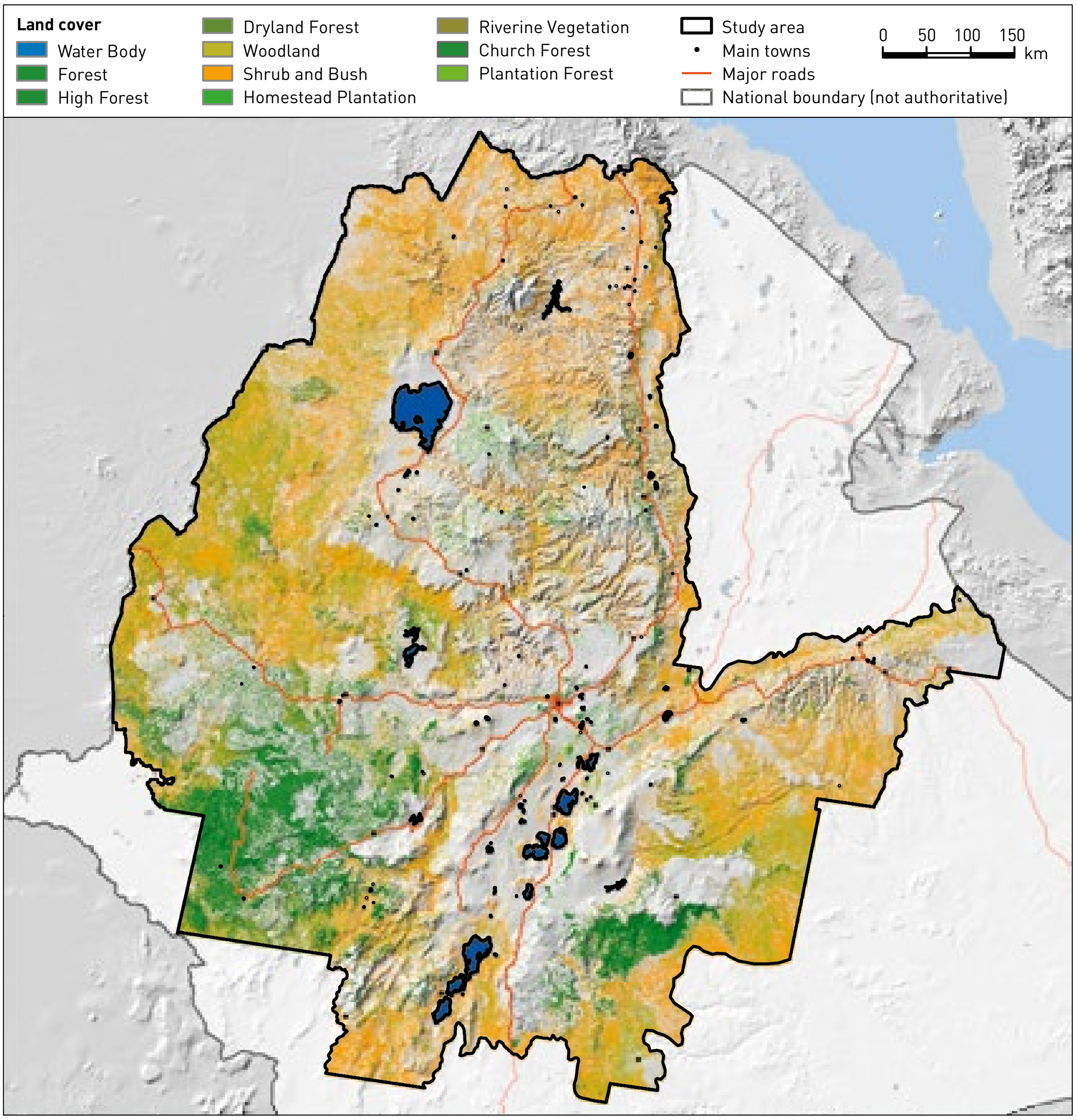
The woody vegetation landscape, in the context of the present mapping scheme, includes forests, woodlands, and shrub and bushes. The total area covered by woody vegetation is 284,354 km^2, nearly half of the study area. Within the woody-vegetation landscape, the forest landscape includes the high forests, dryland forests, plantation forests, mixed forests, church forests, homestead plantations, and riverine forests.

Mapping of these land covers was done by applying the minority and majority concept, which usually results in a high mapping accuracy.

The woodland vegetation is mapped with a different detail of classification (i.e., open and dense) and covers 27,629 km^2 (open) and 57,504 km^2 (dense), which together account for nearly one third of the woody landscape. Also the shrub and bushlands were mapped as open or dense, covering 86,428

FIGURE 6

The woody vegetation landscape in the study area



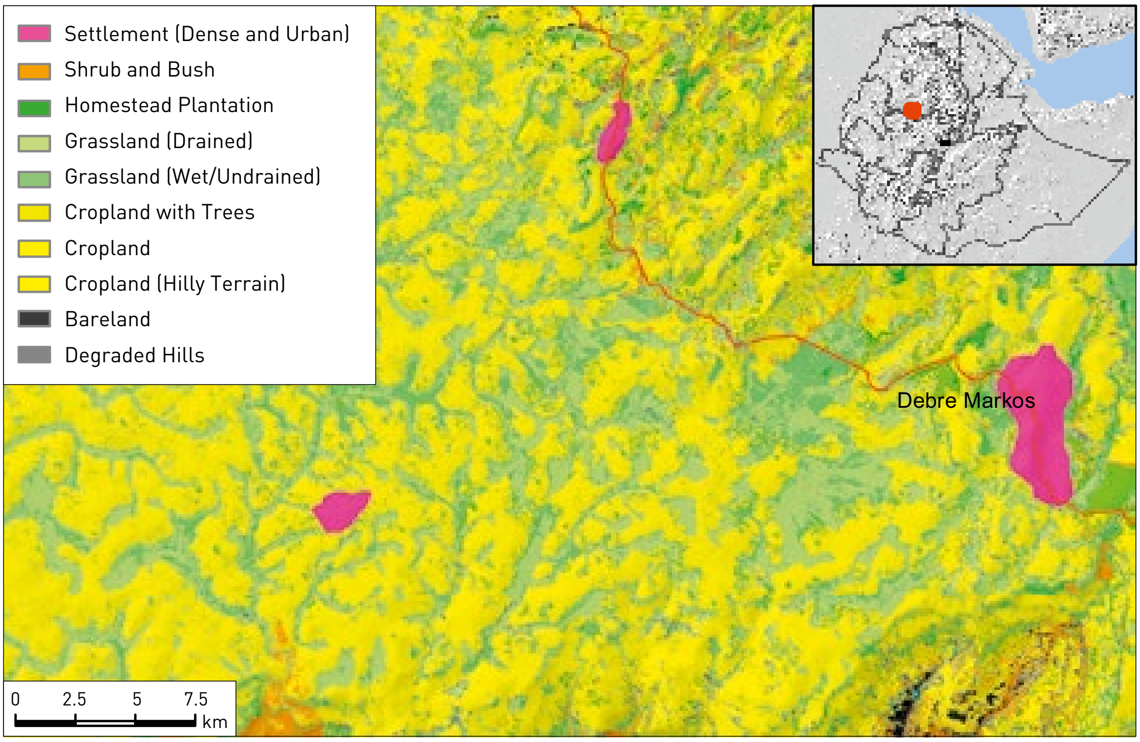
km² (open) and 48,642 km² (dense), accounting together for nearly half of the woody landscape.

The rainfed cultivated landscape

Based on the present scheme of classification, the rainfed cultivated landscape is a land feature that represents entirely rainfall-dependent crop growing fields, including all types of croplands except irrigated fields. Even though croplands in the highland regions are rainfed, there is an insignificant proportion of irrigated (351 km²) land. However, this figure only represents irrigated fields that could be identified with Landsat imagery through

FIGURE 7

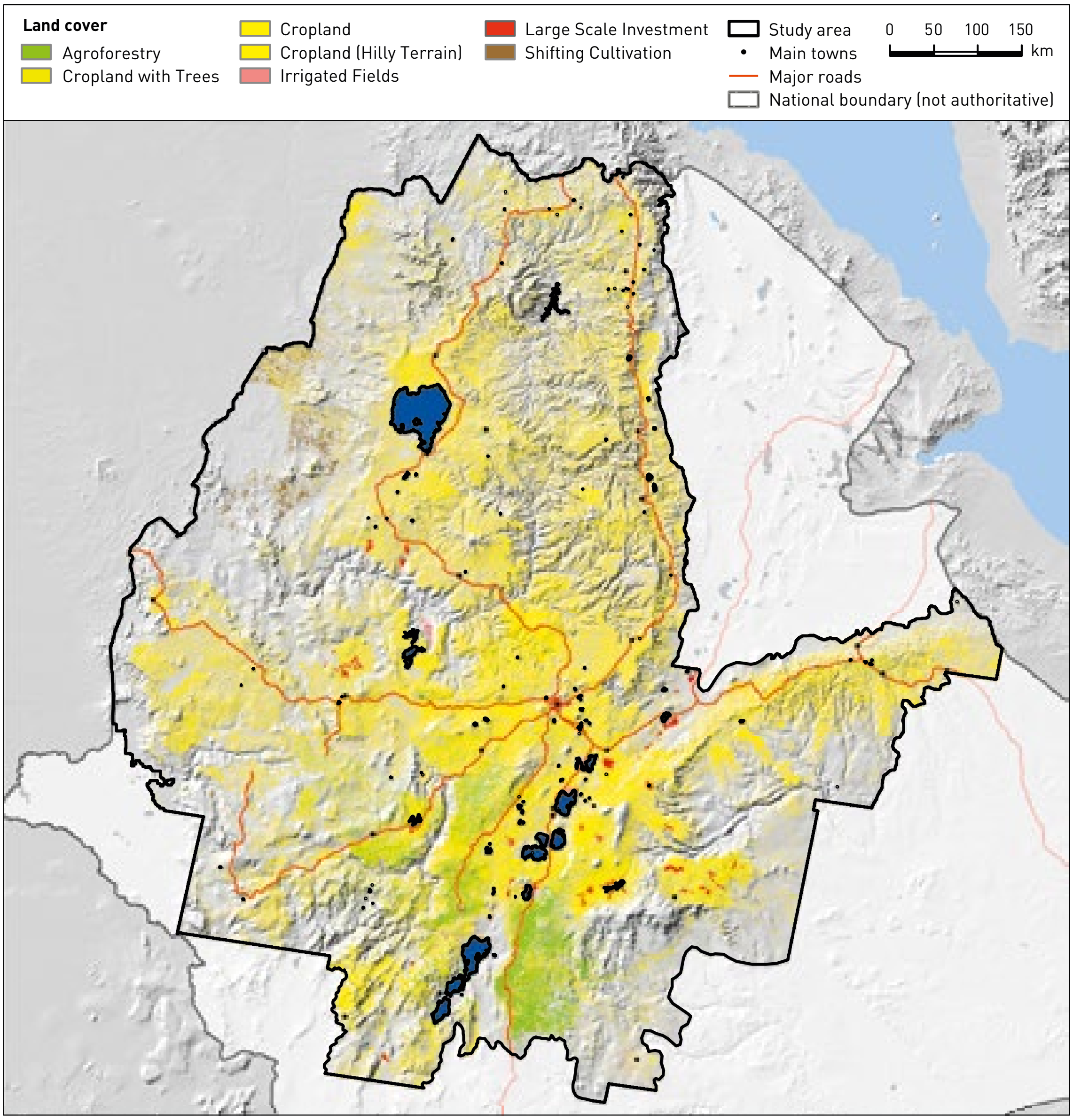
A landscape dominated by rainfed cropland in the study area (detail)



Example of a cropland area with trees

FIGURE 8

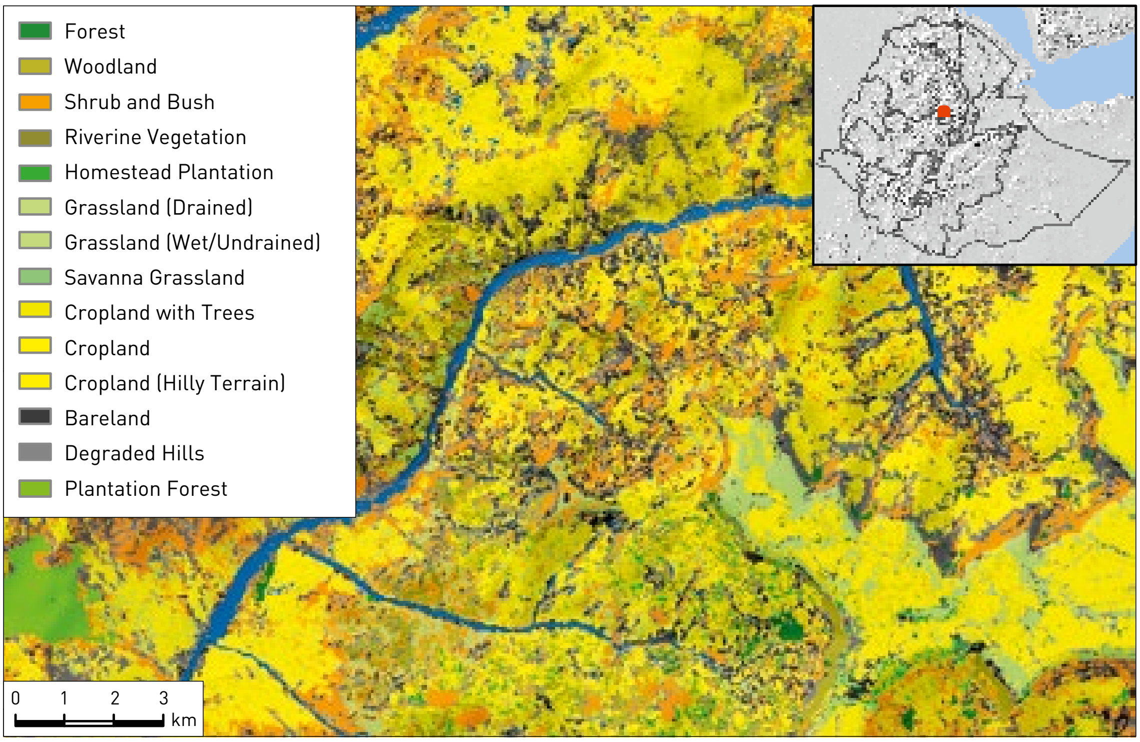
The rainfed croplands in the study area



the described approach. More irrigated fields may exist than indicated, but reliable multi-seasonal remote sensing imagery would be required to map them. The total area covered by the rainfed cultivated landscape is 218,709 km^2, which accounts for one third of the study area. Amongst the rainfed cultivated landscapes, the study identified four distinct cropland categories: croplands without trees (165,124 km^2), croplands with trees (44,462 km^2), croplands in hilly terrain (4,514 km^2), and shifting cultivation (2,807 km^2), all of which are managed by smallholder farmers. Large-scale based cultivations, often leased by investors and/or owned by the government, are also mapped, and cover about 1,803 km^2.

FIGURE 9

Example of a mixed landscape complex in the highlands of Ethiopia (North Shewa, Jema Valley)



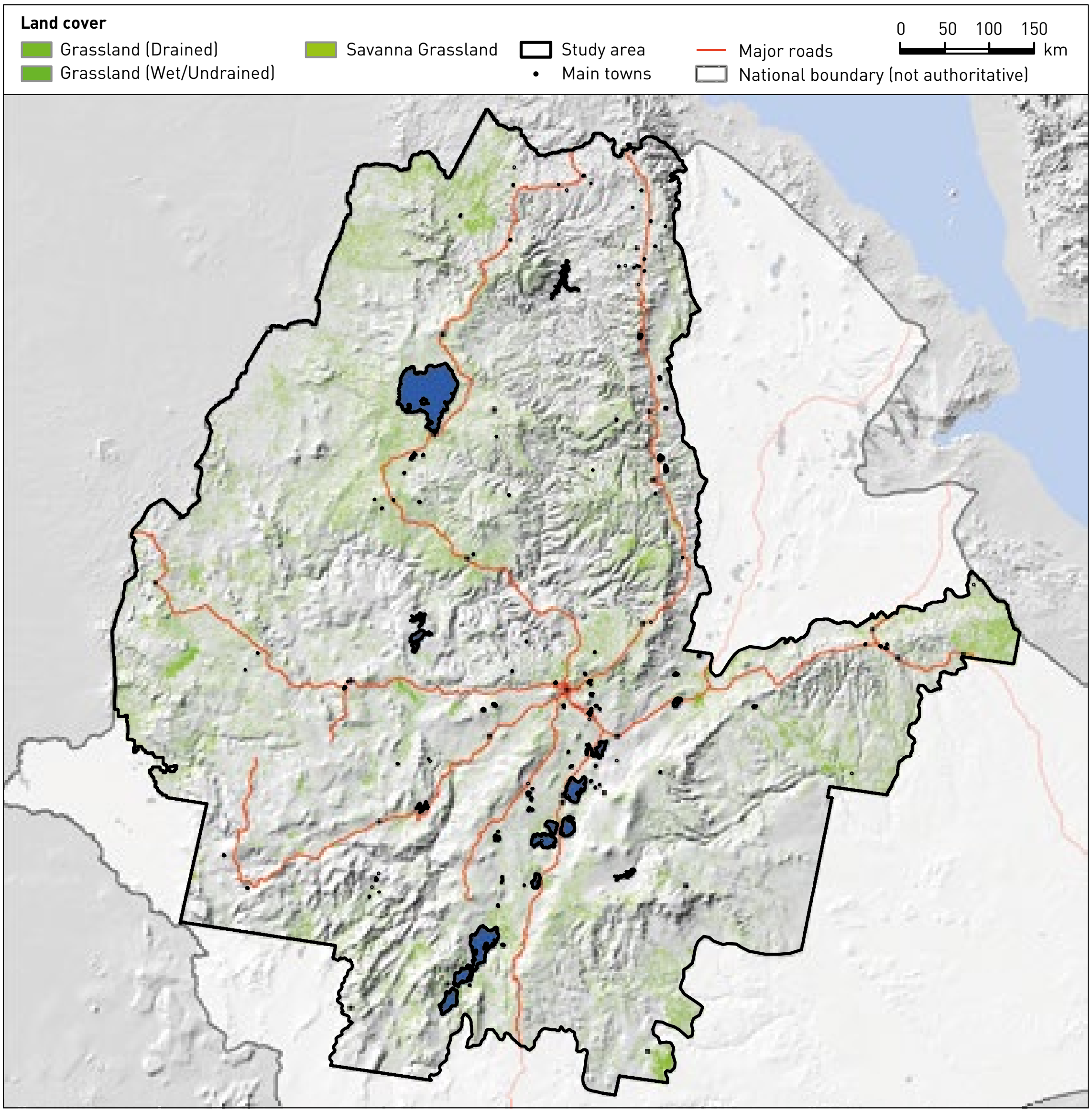
The grassland landscape

In the context of this study, grasslands are land features primarily covered by herbaceous plant species, and often existing as open fields that rarely show individual trees. Extensive grasslands are mostly found in depressions and floodplains, which are commonly vegetated for longer periods of the year. Such grasslands are easily separable from croplands and were classified as un-drained or as wet (less-drained) grasslands. Un-drained grasslands, which are located between cropland plots, degraded hills, and on sloping but non-cultivated landscapes, were difficult to separate from cropped lands, resulting in lower mapping accuracy of these types of land features. Wet grasslands cover


Example of a wet grassland

FIGURE 10

The grassland landscape of the study area



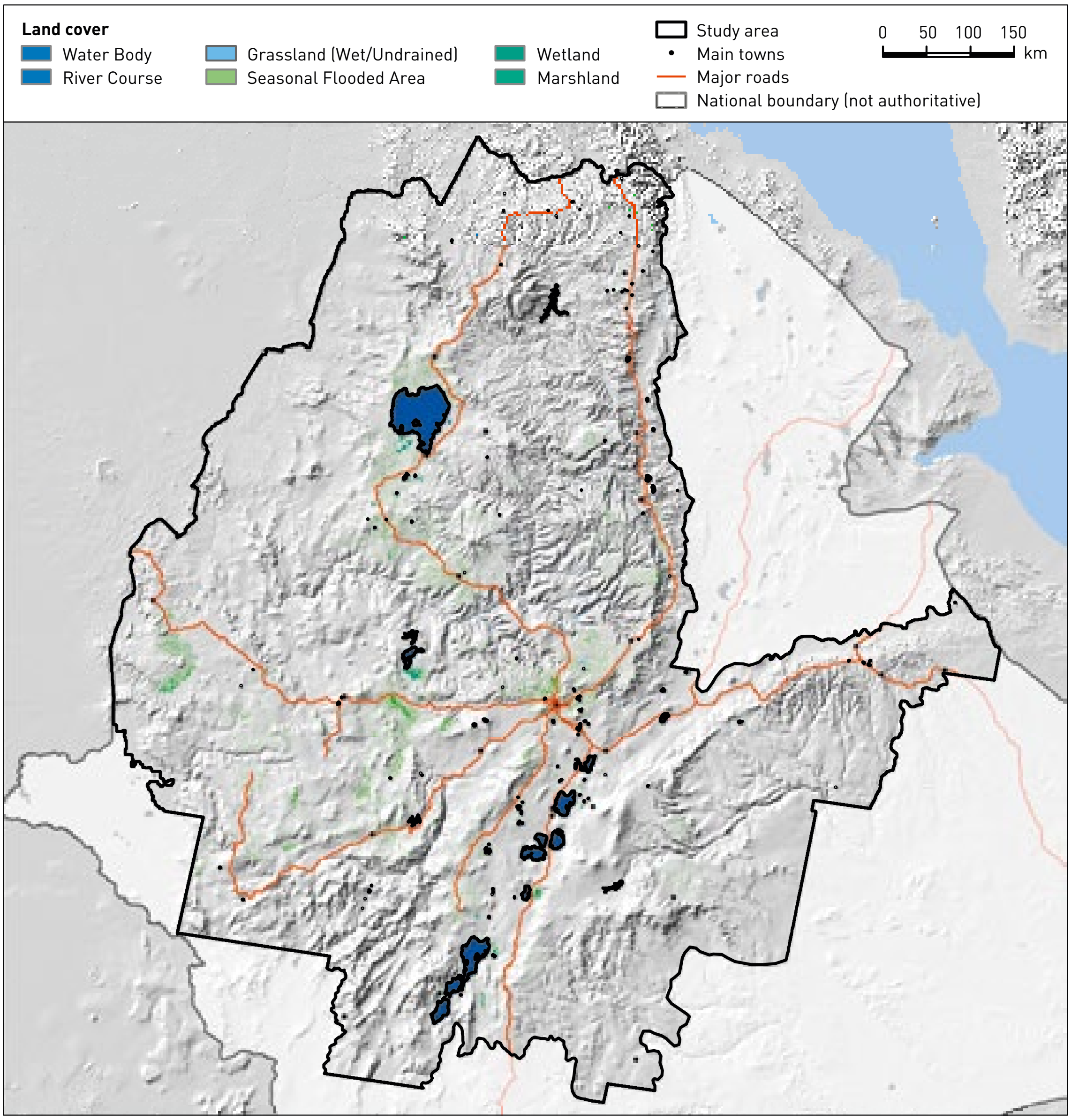
7,101 km^2, drained grasslands cover 51,284 km^2, and savanna grasslands cover 100 km^2, accounting together for 9.53 per cent of the study area.

The wetland landscape

The wetland landscape includes water bodies (natural and artificial lakes, ponds, reservoirs, dams, and rivers) and swamps and marshes. The open water bodies (lakes, reservoirs and ponds, perennial rivers) cover 6,550 km^2, and swamps and marshes cover 919 km^2. The total wetland landscape covers 1.22 per cent of the study area (*Figure 11*).

FIGURE 11

The wetland landscape of the study area



Example of a wetland ecotope

Agroforestry

Agroforestry landscapes are found extensively in the Gedio, Gurage, Jima Zone, and other southern regions. They are dominated by trees with coffee, inset (false banana), chat (khat, a leaf drug), mango, and avocado. These land features cover 13,444 km^2 and accounts for 2.19 per cent of the study area.

Bare lands

In the context of this study, bare lands are barren surfaces where vegetation hardly exists. They are non-vegetated and non-productive landscapes found largely along riversides, quarry and construction sites, riverbeds, and degraded lands. The total area covered by these types of land features is 13,098 km^2, and accounts for 2.13 per cent of the study area.

Exposed rock

In the northern part of the country there are areas where the degradation process reaches to a stage where the parent material surfaces. The total area mapped as exposed rock covers 2,424 km^2, and accounts for 0.37 per cent of the study area.

River courses

With the 30 m resolution of the Landsat data and the applied mapping approach, most of the river courses could be mapped unless dense riverine vegetation hindered the detection of water. The total area of the river courses covers 731 km^2.

Afro-alpine vegetation

There is a unique altitudinal range where these land features exist, simplifying the mapping of afro-alpine vegetation. Commonly afro-alpine regions are covered by herbaceous plant species (rarely by shrub/bush or Ericaceous trees) at altitudes above about 3,400 m/asl. The total area covered by these land features is 2,483 km^2, which accounts for 0.40 per cent of the study area.

Settlements

Settlement areas (mainly urban centres as well as clustered and dense rural settlements) have been identified and mapped. The total area covered by settlements is 1,881 km^2, which accounts for 0.31 per cent of the study area.

Others

Land features other than those mentioned above (e.g., mining and quarry sites, area covered by invasive species, etc.) are insignificant in terms of area coverage, but were also considered in the mapping process. The total area covered by such land features is 47 km^2, which accounts for 0.01 per cent of the study area.

2.1.4 Conclusion and recommendations

The main methodological approach implemented to map this complex landscapes at the required scale was the majority and minority concept of landscape segregation that translated into the HICU-based mapping. This approach enabled authors to capitalize on the unprecedented qualities that exist in the satellite images used. The employment of such an 'exclusion-based' approach (i.e., sub-setting of the image and gradually reducing the minorities/majorities) can be considered as a breakthrough in deriving important land cover information in heterogeneous landscapes, such as this rainfed agricultural area of Ethiopia.

The present study has achieved the extraction of 50 distinct land features from medium (30 m x 30 m pixels) resolution satellite images. Only for simplicity's sake were all of these classes not considered in the maps and statistics. However, the digital data contains all 50 classes as independently mapped land features. While a pixel based accuracy assessment of the land cover data could not yet be produced due to time restrictions, the comparison with Google Earth high resolution imagery shows satisfactory results. Even though the accuracy of the different land cover classes can vary between classes and regions, the comparison with other sub-national (regional) and national land cover datasets clearly shows a significant improvement of this dataset.

2.2 Component 2: Conservation structure mapping

2.2.1 Detection of conservation structures from high resolution satellite images

Conservation structure mapping approach

Authors attempted to apply an automated model that can map physical soil and water conservation structures (fanya juu bunds, soil bunds, and stone terraces) on croplands of the Ethiopian Highlands (Mekuriaw 2014). The model was developed using the very high spatial resolution imagery (less than 1 m) obtained from Google Earth, field verification, image analyst software (i.e., ArcGIS, ERDAS IMAGINE, and SDC Morphology Toolbox for MATLAB), and statistical analyses.

The mapping of the structures was performed using the following procedures: first, a high-pass spatial filter algorithm was applied to the target image to detect linear features. Second, morphological processing (e.g., opening, thinning, closing, and skeletonisation using structuring elements) was used to remove unwanted linear features. Third, the raster format of linear features was vectorised. Fourth, the target area was split into hectares to get land units of similar size. Fifth, the vectorised linear features were split per hectare, and each line was then classified according to its compass direction. Sixth, the sum of all vector lengths per class of direction per hectare was calculated. Finally, the direction class with the greatest length was selected from each hectare to predict the physical SWC structures.

This model was developed and calibrated within a PhD study – readers can refer to Mekuriaw (2014) for more information on the approach and methodology, and obtained results.

Results of the conservation structure mapping within this study

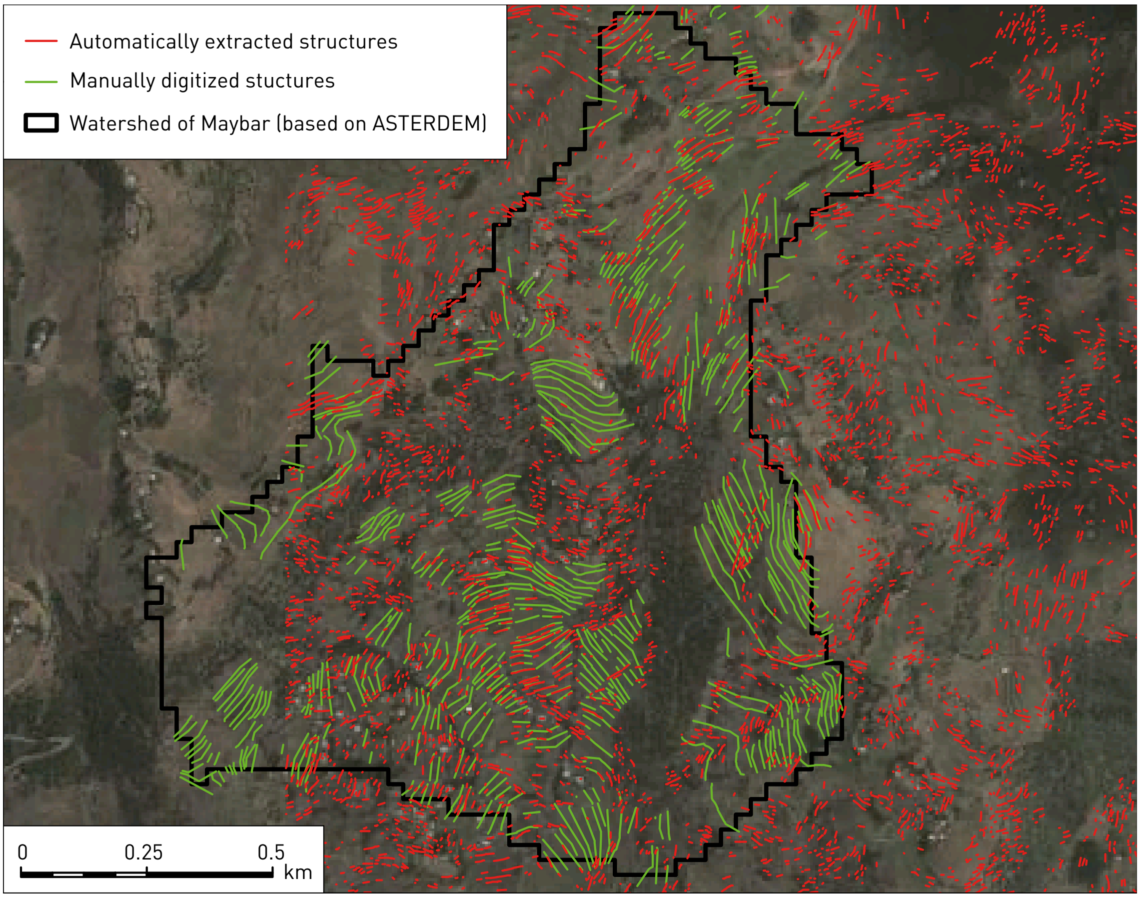
Unfortunately the mapping of conservation structures within this study did not go as expected. The linear features as mapped by the approach described above were compared with conservation structures that were manually digitized from Google Earth imagery (*Figure 12*). The following issues were found to be related to the poor performance of the automated mapping of conservation structures:

- **Acquisition date of the high resolution imagery:** the accuracy of the applied approach varies according to the season of high resolution imagery acquisition. The best detection of structures is possible when the images are taken after harvest and before the growing season. By covering a large area, not all of the images were acquired at the optimal season, resulting in an inaccurate structure mapping;

- **Land cover data:** applying the suggested approach only within land cover classes where structures are known to occur increases the accuracy of their detection. However, this requires a detailed land cover dataset that represents small land cover features that can be observed in high resolution imagery. With a

FIGURE 12

Comparison of manually digitized structures (green) and automatically extracted structures (red)



resolution of 30 m, the difference in resolution was too big to allow for an accurate detection of structures in this study, and;

- **Computer resources:** working with high resolution imagery increases computational time heavily. Within the project time, it was not possible to further invest on adaptions of the automated structure mapping approach for overcoming other aforementioned limitations.

With the remote sensing approach of mapping existing conservation structures not able to provide the required information, authors had to find another way of obtaining information on their distribution. This is described in the following sections.

2.2.2 Distribution of current conservation structures

To model the current distribution of existing conservation structures, an expert-based approach was applied that first defined the amount in each administrative zone, and then used a combination of spatial proxies to model the locations where they occur.

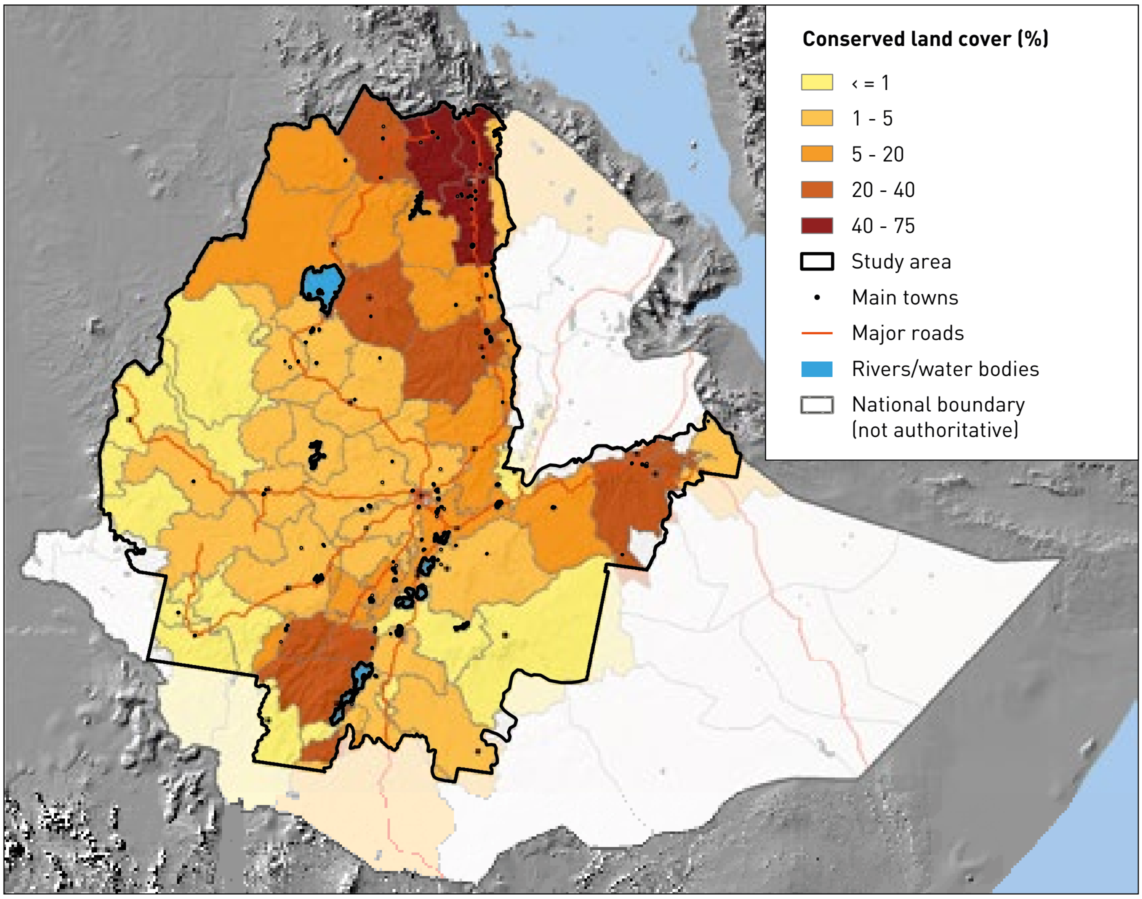
Definition of occurrence of conservation structures

To define the occurrence of conservation structures, five experts with vast field experience defined which land cover classes with conservation structures exist (besides cropland, in some of the zones conservation structures also exist on bushland, grassland, and degraded hills), for each administrative zone. Then, the share of these land

FIGURE 13

The share of the existing conservation structures by land cover classes

(For most of the zones the structures only occur on croplands. However, in central Tigray, Eastern Tigray, South Tigray, North Wello and South Wello, structures exist on cropland, bushland, grassland, and degraded hills)



cover classes conserved for each zone was defined (see *Figure 13*).

Spatial proxies and their combination to model conservation structures

Together with the SWC experts, authors selected spatial proxies from the datasets available in Ethio-GIS II that could serve to model the distribution of conservation structures at the pixel level. Three datasets were identified that could be used to approximate the spatial distribution of the structures: land cover, slope, and accessibility:

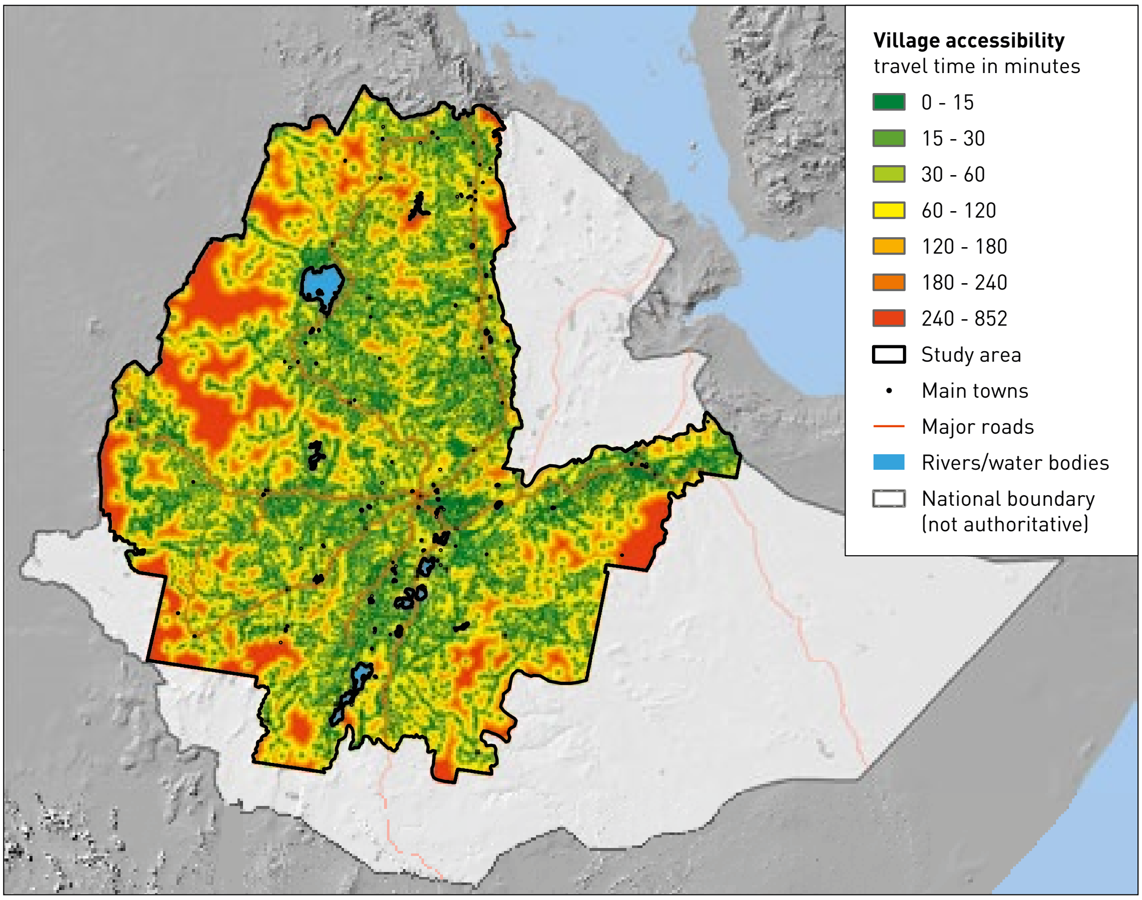
Land cover: for each administrative zone the land cover classes within which conservation structures exist were defined. In Central Tigray, Eastern Tigray, South Tigray, North Wello, and South Wello, conservation structures occur on cropland, but also in areas with shrubs and bushes, grasslands, and degraded hills. In the other administrative zones, conservation structures only exist in croplands. *Figure 13* shows the share of these land cover classes that contain conservation structures.

Slope: within the defined land cover classes, the distribution of the conservation structures also relates to slope. Seven slope classes that affect the occurrence of conservation structures were defined: **1)** 0–2 per cent; **2)** 2–5 per cent; **3)** 5–8 per cent; **4)** 8–16 per cent; **5)** 16–30 per cent; **6)** 30–45 per cent, and; **7)** >45 per cent. The occurrence of conservation structures within each of these slope classes depends on the total amount of terraces that occur within each administrative zone. Terraces are found more commonly on hillsides with

FIGURE 14

Village accessibility map

(Colours indicate travel time in minutes from any location to the next settlement, assuming that the fastest means of transportation is chosen)



slopes from 16–30 per cent, but with increasing structure occurrence, they can also be found (in order of more common occurrences) on slopes from 30–45 per cent, then 8–16 per cent, >45 per cent, and 5–8 per cent. The study assumed that structures did not occur in areas with slopes <5 per cent.

Village accessibility: using just land cover classes and slope classes did not allow authors to model the distribution of the conservation structures satisfactorily. An additional spatial proxy was needed that would represent areas where policies and development projects focusing on the construction of conservation structures are more likely to be implemented. A village accessibility layer, indicating how much travel time in minutes is required to reach the closest settlement (assuming the fastest possible means of transportation) for each pixel was found to be a good proxy.

Village accessibility was calculated following the approach described by Heinimann (2006), which includes information on land cover, slope, road data, rivers, and village points to estimate, for each pixel, the travel time to the closest village point assuming that the fastest means of land-based transportation (e.g., travelling by car on roads and on foot for other land cover classes) is used. *Figure 14* shows the village accessibility calculated for the study area. This continuous layer was also reclassified into seven accessibility zones with class breaks. Authors assumed that conservation structures are more likely to occur in more accessible areas (less travel time from villages).

To model conservation structure distribution within the study area, a spatial combination of the different proxies was performed: land cover classes with conservation structures were combined with the slope and village accessibility classes. This resulted in a dataset where each pixel had the following information: land cover class, grade of slope class, and travel time to the next settlement class. This information was summarized for each administrative zone, and revealed which class combinations occurred within each zone, as well as the area covered by each occurring combinations. The conservation structures were then distributed within these class combinations until the amount of conserved area within the administrative zone as defined by the experts was reached. Conservation structures were first assumed to occur on more sloping lands (8 per cent and steeper) and close to settlements/roads (rather accessible). If only few conservation structures exist within a zone, the terrace distribution model assumed that the terraces occur on steep slopes only and rather close to the village. The more conservation structures exist within a zone, terraces were also assumed to be on less sloping land and also further away from the villages (less accessible).

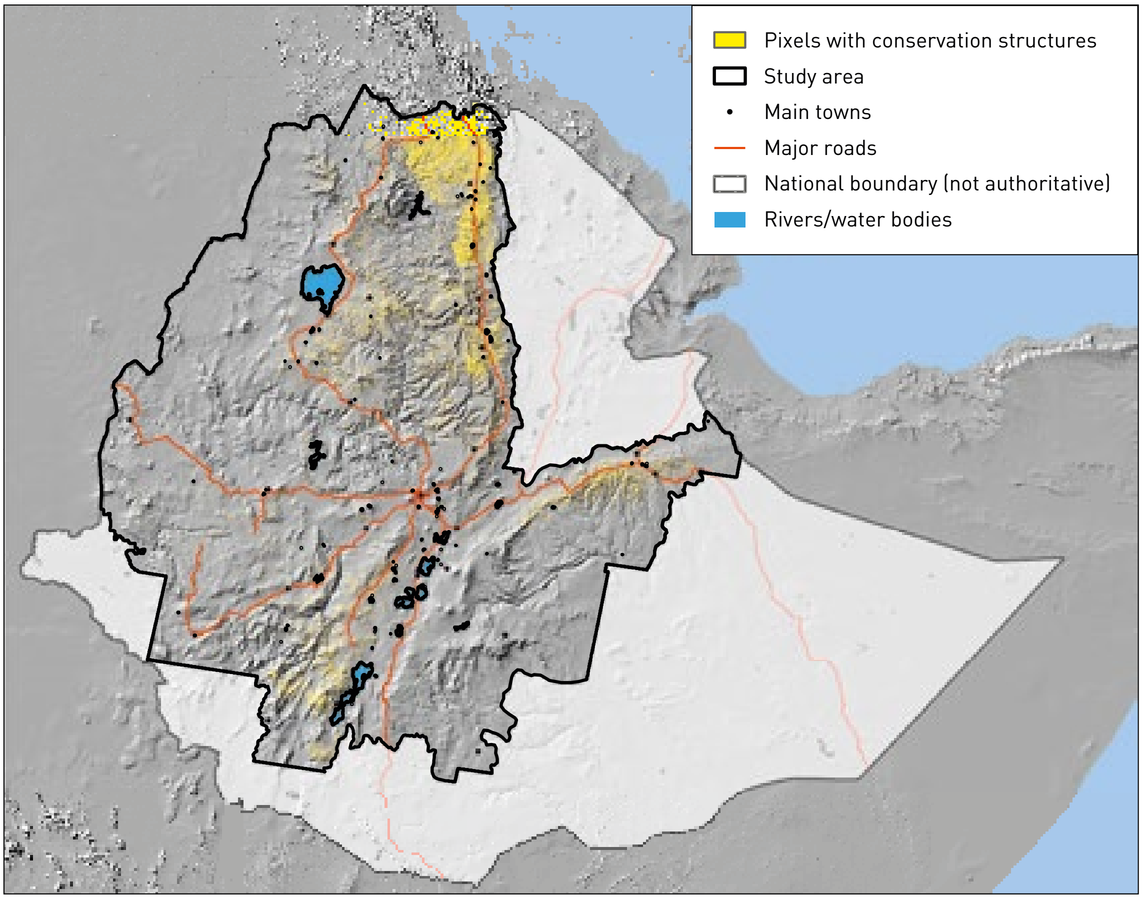
Result of the conservation structure modelling

The mapped conservation structures resulted in a distribution of conservation structures as shown in *Figure 15*.

The pattern that *Figure 13* (share of conservation structures per zone) revealed can also be seen on this map, except terrace distribution is now displayed by individual pixels. It is important to note that this pixel based map is actually not accurate at the level of individual pixels due to the use of proxies to distribute the structures in the landscape. This is especially the case in the zones where only a small share of the landscape shows conservation structures. In zones with a larger share of existing conservation structures, the pixel based information appears to be more accurate. Considering this

FIGURE 15

Modelled distribution of conservation structures within the study area



level of generalization, the information provided by this model can be assumed to be accurate from wereda/zone level and upwards. This limitation should be kept in mind when interpreting the results of the analyses.

2.3 Component 3: Estimation of current soil erosion

2.3.1 Background and methods

Soil erosion is considered the major driver of land degradation in the areas of rainfed agriculture of Ethiopia. Being able to model erosion for these areas can therefore be considered a proxy for estimating the current (and future) speed at which land degradation takes place. In most cases soil erosion is assessed using empirical models, with the Universal Soil Loss Equation (USLE) being the most commonly used model in Ethiopia. The reason for the high number of studies applying the USLE lies in its simplicity (relatively few factors are considered) in combination with its ability to provide reliable results of gross soil loss from a given slope. Such a combination is a prerequisite in areas where reliable erosion estimate data is scarce, especially when assessing large extents.

The USLE estimates soil erosion based on the following factors/datasets:

- **R:** 'Erosivity', describes the erosive forces that occur. For this study area, it is mainly related to rainfall amount and intensity, and can be derived from precipitation data;
- **K:** 'Erodibility', describes the susceptibility of the soils to erosion, and can be derived from information on soil types;
- **P:** The management factor, describes human interventions that affect soil erosion. For example, soil and water conservation measures that can reduce soil erosion are considered here;
- **C:** The cover factor, describes how different land cover classes affect soil erosion, and can be derived from land cover classification, and;
- **LS:** The slope factor, including both steepness and length. While steepness can be derived from a DEM, length needs to be measured or estimated.

However, in this case study the USLE was found to be inappropriate due to two reasons. Firstly, slope length cannot be measured considering the large area covered. Also, estimates of length were not assumed to be accurate enough considering the size and resulting heterogeneity in terms of land use practices and related land covers and topography. Secondly, and more importantly, the USLE only provides an estimate of gross soil erosion from a given slope. In this study however, authors planned to derive crop production from soil depths, which are not only affected by erosion, but also deposition originating from soils transported from upslope areas.

Due to these shortcomings, this study used the Unit Stream Power Erosion Deposition (USPED) model (cf. Mitasova et al. 2001). While compared to the USLE, very little research has been performed using the USPED. However, it has the potential to overcome the two aforementioned disadvantages of the USLE while keeping its simplicity by mostly using the same parameters as the USLE. The R, K, P, and C factor of the USLE are also used in the USPED. Only the LS factor is replaced, so that no assumptions on the slope length need to be performed. By replacing the LS factor of the USLE, the USPED model not only considers erosive forces, but also the sediment transporting capacity of the runoff, which allows estimations of both soil erosion and deposition (Garcia Rodriguez & Gimenez Suarez 2012).

When implementing the USPED model in GIS, the LS factor of the USLE is replaced by a combination of slope and flow accumulations (indicating for each pixel, the upslope contributing area/pixels). This case study followed the approach described by Mitasova et al. (1996) and Mitasova et al. (2001), which provided a detailed guide on how to implement the USPED model in GIS. However, two shortcomings were found (noted below) during implementation that related to the calculations performed/GIS functions used, so an adaptation of the flow accumulation data had to be performed for obtaining appropriate estimates of soil erosion/deposition.

First, all pixels representing rivers and streams (flow accumulation >= 25 pixel areas) had to be excluded from the analysis as unrealistic erosion/deposition rates were obtained along the rivers and streams (related to the GIS functions used when estimating soil erosion/deposition). This adaptation can be justified by the interest in finding out what happens on the land (cropland): it was assumed that once the eroded soil reaches the rivers it is gone, and even if depositions occur within the river, the soil is no longer available for cultivation. This assumption is not fully correct, as there may be areas of deposition on the edges of rivers/lakes that may become available for cultivation, but these cases are the exception, making this modification acceptable.

Second, pixels without any upslope contributing areas (local maxima in height) show a value of zero in the flow accumulation dataset. Based on the calculations, this zero value also results in an erosion estimate of zero, which does not represent the reality. To overcome this, authors added a value of 0.5 to the flow accumulation dataset. This value allows for the accounting of the flow accumulation that already occurs locally in the uppermost pixels, and thus allows for estimates of erosion that may occur in those pixels.

2.3.2 Calibration of the USPED model

Calibration sites

Authors calibrated and validated the USPED model for five catchments of the Soil Conservation

FIGURE 16

Location of the five SCRP catchments (Andit Tid, Anjeni, Dizi, Hunde Lafto, and Maybar)

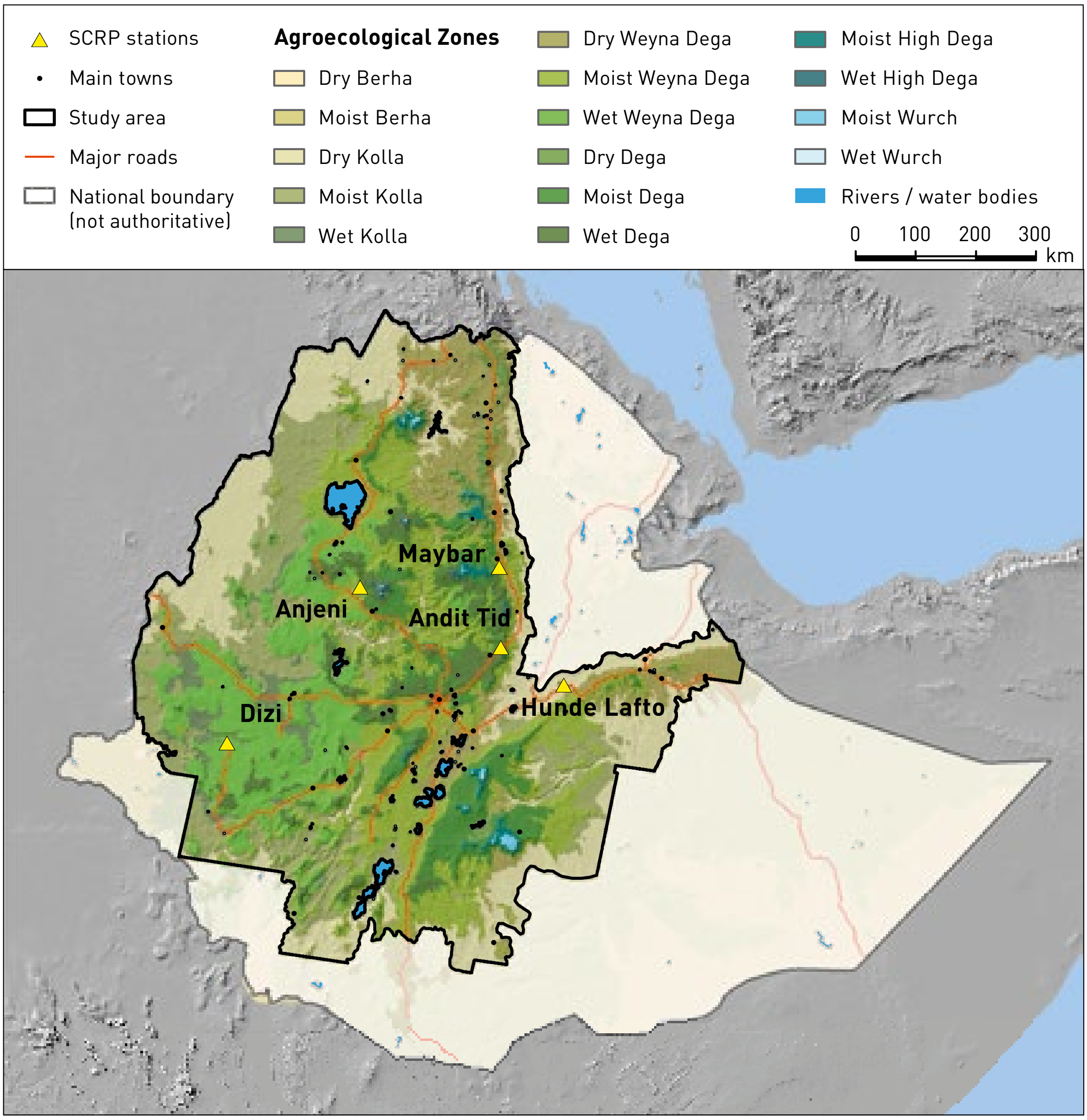


FIGURE 17

Agro-ecological zones of Ethiopia, divided according to altitudinal and rainfall zones
(from Hurni 1998)
(This study focused on the zones at altitudes above 500 m, as rainfed agriculture only occurs in very limited locations beneath that)

Altitude in metres above sea level (m asl)	Less than 900	900 to 1400	More than 1400
More than 3700		**MOIST WURCH** A: None but wildlife C: None S: Black, shallow T: Hypericum quartinianum, Hypericum roeperianum	**WET WURCH** A: None (frost limit) C: None S: Black soils, little disturbed T: Mountain grassland
3700 to 3200		**MOIST HIGH DEGA** A: Only barley, 1 cropping season per year C: Drainage rare S: Black soils, degraded T: Erica Hypericum	**WET HIGH DEGA** A: Only barley, 2 cropping seasons per year C: Widespread drainage ditches S: Black soils, highly degraded T: Erica Hypericum
3200 to 2300	**DRY DEGA** A: Barley, wheat, pulses C: Traditional moisture conservation measures S: Grey-brownish grey T: Olea europaea, Maytenus undata, M. senegalensis	**MOIST DEGA** A: Barley, wheat and pulses, 1 cropping season per year C: Some trad. terracing S: Brown clay soils T: Juniperus, Hagenia, Podocarpus	**WET DEGA** A: Barley, wheat, nug, pulses, 2 cropping season per year C: Widespread drainage ditches S: Dark brown clay soils T: Juniperus, Hagenia, Podocarpus, Bamboo
2300 to 1500	**DRY WEYNA DEGA** A: Wheat, tef, rarely maize C: Terracing widespread S: Light brown to yellow soils T: Acacia trees	**MOIST WEYNA DEGA** A: Maize, sorghum, tef, inset rare, wheat, nug, daguss, barley C: Trad. terracing S: Red-brown soils T: Acacia, Cordia, Ficus	**WET WEYNA DEGA** A: Tef, maize, inset in W parts nug, barley C: Drainage widespread S: Red clay soils, deeply weathered, gullies frequent T: Many varieties, Ficus, Cordia, Acacia, Bamboo
1500 to 500	**DRY KOLLA** A: Sorghum rare, tef C: Water retention terraces S: Yellow sandy soils T: Acacia bushes and trees	**MOIST KOLLA** A: Sorghum, rarely tef, nug, dagussa, groundnut C: Terracing widespread S: Yellow silty soils T: Acacia, Erythrina, Cordia, Ficus	**WET KOLLA** A: Mango, taro, sugarcane maize, coffee, citrus C: Ditches frequent S: Red clay, highly oxidized T: Milicia excelsa, Cyathea manniana
Below 500	**DRY BERHA** A: None (except irrigation areas) C: None S: Yellow sandy soils T: Acaciabushes	**MOIST BERHA** A: Seasonal rainfed agriculture possible C: Burning grasses common, no wind erosion S: Silty and clayey, mainly black T: Ziziphus pubescens, Antiaris toxicaria, Erythroxylum fischeri	

Annual rainfall (millimetres)

Research Programme (SCRP), some of them managed by the Amhara Regional Agricultural Research Institute in collaboration with WLRC, which provide long-time series of erosion measurements as well as measurements of total sediment yield in these catchments. The locations of the five SCRP watersheds (Andit Tid, Anjeni, Dizi, Hunde Lafto, and Maybar) are shown in *Figure 16*.

The SCRP catchments are located in different agro-ecological zones of the Ethiopian Highlands considered in this study (see *Figure 16* and *17*) and are therefore representative for this study area. The calibration of the model for the different agro-ecological zones is a prerequisite for reliable estimates of soil erosion/deposition. Within each agro-ecological zone similar precipitation patterns, land covers, and crop types occur, both of which are important determinants of soil erosion/deposition.

Input datasets

For each of the SCRP stations, the initial parameters used in the USPED model were derived from different studies using the USLE to provide erosion estimates. As the USPED model is mostly based on the same parameters as the USLE, a similar calibration of the parameters can be assumed. The list below provides information on the initial values attributed to the different parameters and the datasets used to derive the parameters:

TABLE 3

Dominant soil types considered and the corresponding K factors used for the initial calibration of the model

(Hurni 1985)

Soil types	Suggested K factor ranges
Alisols	0.30–0.40
Andosols	0.10–0.20
ArenosolsS	0.30–0.40
Chernozems	0.10–0.20
Calcisols	0.30–0.40
Cambisols	0.15–0.25
Fluvisols	0.15–0.30
Gypsisols	0.30–0.40
Leptosols	0.15–0.25
Luvisols	0.20–0.30
Lixisols	0.20–0.30
Not defined	Case study average
Nitisols	0.20–0.30
Phaeozems	0.10–0.20
Regosols	0.15–0.30
Solonchacks	0.20–0.30
Solonetz	0.30–0.40
Vertisols	0.10–0.20

K-factor (erodibility): Soil erodibility is related to soil types and can therefore be estimated from that information. This study used data on the dominant soil types provided by the EthioGIS II database. Initial K-factors that served as input to the calibration were derived from the study of Hurni (1985), showing a relationship between soil colour and the K factor. The dominant soil types used in this study, as well as the initially assigned K-factors are shown in *Table 3*.

P factor (management): While a variety of management options exists that allow for a reduction of soil erosion (e.g., mulching, no tillage, different ploughing techniques, constructions as terraces, soil bunds, fanya juu bunds), only physical conservation structures (terraces, soil bunds, and fanya juu) were considered in the P-factor. For the other management options, no spatial information at pixel level on their distribution was available, which prevented their inclusion in the study.

To obtain information on the distribution of SWC structures for the calibration of the USPED model, the structures were digitized for each of the SCRP catchments from high resolution Google Earth imagery. A series of calculations were then required to translate the linear information to a pixel based P-factor, as described below:

1. Calculation of the total length of conservation structures for each 30 m x 30 m pixel.

2. Calculation of the spacing between the terraces using the following function:

   $$y = 900 / x$$

   , with *900* being the pixel size in square meters, *x* the total terrace length in meters, and *y* the spacing of the terraces.

3. Definition of optimal conservation structure spacing, based on the findings of Hurni (1981), showing the optimal spacing of conservation structures in relation to slope. These findings

FIGURE 18

Optimal spacing of conservation structures in relation to the slope
(derived from Hurni 1981)

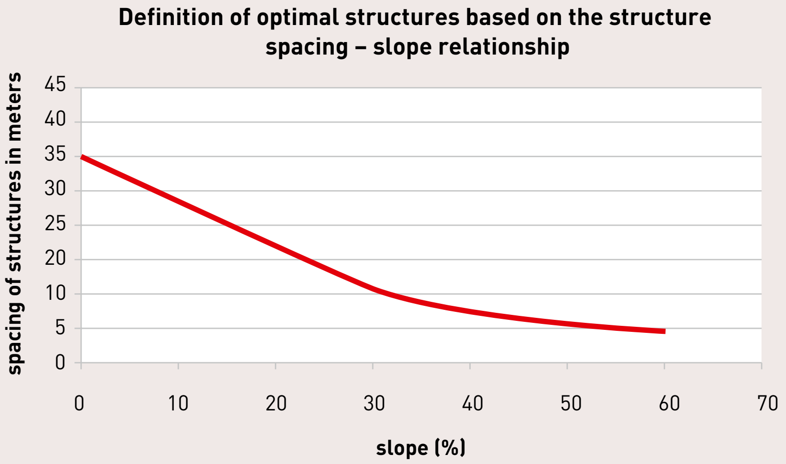
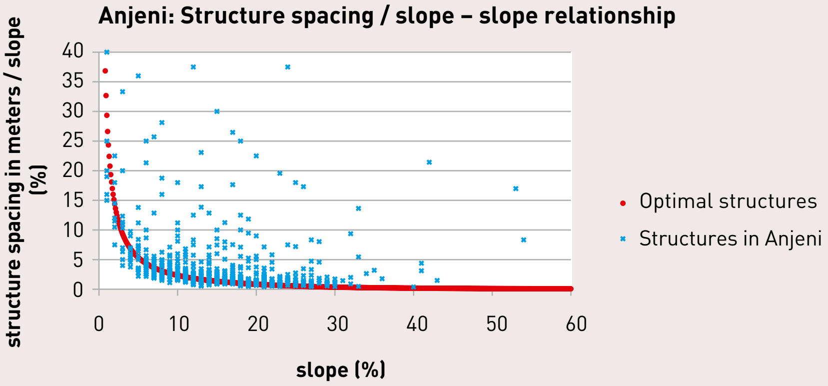


FIGURE 19

Comparision of the quality of observed structures (based on the spacing of the structures in relation to the slope) with optimal structures (red line)



were translated into the following formulas (*Figure 18* also shows the optimal spacing of terraces in relation to slope), with slopes above 60 per cent not being considered:

- For slopes < 25%:

$$y = 30 - (0.65619 * x)$$

, with *x* being the slope (%), and *y* the spacing in meters between structures

- For slopes >= 25%:

$$y = 760 / x^{1.25}$$

, with *x* being the slope (%), and *y* the spacing in meters between structures.

4. By dividing the spacing of the observed structures by slope and then comparing it with the spacing of optimal structures divided by slope, authors could assess how much existing struc-

tures deviate from optimal structures. *Figure 19* shows this comparison in Anjeni (in red the optimal spacing of structures and in blue the observed spacing of the structures). Blue crosses below the red curve show an even lower spacing than the optimum, while blue crosses above the curve show a spacing below the optimum

5. The comparison displayed in *Figure 19* allowed authors to attribute a P-factor to the observed terraces based on their deviation from the red curve, in the following way:

   - Deviations <= –100 were attributed a P factor of 1 (not efficient in preventing soil erosion)
   - For deviations > –100, the following formula was used:

$$P\text{ factor} = -0.0064^{*}\,x + 0.3$$

, with *x* being the deviation of the observed structures from the optimal structures.

C-factor (cover): To derive the C-factor related to land cover, the Landsat-based data created within this study (see *Chapter 2.1*) was used. Based on available literature, initial C-factors for the calibration were assigned, considering the specific land cover classes that occur in the five SCRP catchments.

TABLE 4

USPED parameters for the different SCRP catchments

(Not all land cover and soil types occurring in the study area are listed, as not all of them occur in the catchments)

Parameter	Andit Tid	Anjeni	Dizi	Hunde Lafto	Maybar
Land cover	**C-factor**				
Croplands with trees	0.09	0.17	0.1		
Croplands without trees	0.1	0.2	0.11	0.125	0.1
Drained grasslands		0.11	0.04		0.05
Less drained grasslands		0.1	0.03		0.05
Homestead plantation		0.15			0.075
Woodland open	0.08			0.08	
Woodland dense	0.06			0.06	
Shrub and bushes (dense)		0.1		0.06	
Shrub and bushes (open)					0.05
Forest	0.03		0.02		
High forest			0.01		
Plantation Forest	0.04	0.05			0.05
Afro-alpine vegetation	0.06				
River Course		0			
Soil types	**K-factor**				
Cambisols	0.1			0.11	0.1
Leptosols	0.1		0.1	0.11	0.1
Luvisols		0.25		0.17	
Nitisols			0.12		
Management	**P-factor**				
Structures	Based on the quality of structures (structure spacing - slope relationship)				
Precipitation	**R-factor**				
Annual rainfall	Based on the precipitation – R-factor correlation (Kaltenrieder 2007)				

ASTERDEM (ASTER Digital Elevation Model): To estimate the sediment transport capacity of the water (replacement of the SL-factor of the USLE), and in addition to the factors mentioned above, the USPED requires slope and flow accumulation data, both which can be derived from a DEM. In this study, authors used ASTERDEM (http://asterweb.jpl.nasa.gov/gdem.asp), as it shows the same resolution as the Landsat data used to derive the land cover and thus allows the soil erosion/deposition modelling to be performed at 30 m x 30 m pixel sizes.

Calibration and calibration results of the SCRP catchments

Starting from the parameter values derived from the USLE literature, the USPED model was run for each SCRP catchment, with parameter values adjusted accordingly until the targeted measured sediment yields were obtained. The parameter values that allow for an estimation of the indicated sediment yields and thus provide reliable erosion/deposition estimates at pixel level are provided in *Table 4*.

The calibration and validation showed that all USPED parameter values are rather low when compared to the USLE values. In order to model the targeted sediment yields, the initially defined parameters (derived from USLE literature) had to be reduced substantially for four of the watersheds (Andit Tid, Dizi, Hunde Lafto, and Maybar). Only in Anjeni was this reduction of the parameter values not needed to model yields. However, unlike the other watersheds, there is a big gully within Anjeni. This gully contributes heavily to the total sediment yield, probably as much as one third, but is not represented in the USPED model. Parameter values obtained for the Anjeni watershed are therefore likely to be distorted. As a result, the calibration results of Anjeni watershed were not used for the extrapolation of the USPED model to the whole study area.

2.3.3 Extrapolation and verification of the USPED model

For the calculation of the USPED model for the whole study area, the same input data was used as for the calibration sites to derive the R, K, and C-factor, and to estimate the transporting capacity of the water. Only for the P-factor estimation was no map on the distribution and extent of conservation structures available. It was therefore estimated from the structure distribution model as described in *Chapter 2.2.2*. As this model does not provide information on spacing between conservation

TABLE 5

Agro-ecological zones of calibration sites and source and method of parameter estimation for the agro-ecological zones without calibration sites

Agro-ecological zone	Parameter calibration site	Parameter estimation
Dry Kolla	n/a	Hunde Lafto
Moist Kolla	n/a	Hunde Lafto
Wet Kolla	n/a	Dizi
Dry Weyna Dega	Hunde Lafto	
Moist Weyna Dega	Hunde Lafto, Maybar	Maybar
Wet Weyna Dega	Dizi	
Dry Dega	n/a	Average of Hunde Lafto and Maybar
Moist Dega	Maybar	
Wet Dega	Andit Tid	
Moist High Dega	n/a	Average of Maybar and Andit Tid
Wet High Dega	Andit Tid	
Moist Wurch	n/a	Average of Maybar and Andit Tid
Wet Wurch	n/a	Andit Tid

structures, a P-factor of 0.4 was attributed to the areas where conservation structures were modelled. This again reflects the reduction in sediment yields (i.e., by 60 per cent) in the SCRP catchments after soil conservation was implemented. The extrapolation of the USPED model parameters from the calibration sites to the study area was then performed as described in the following sections.

Estimation of missing parameter values

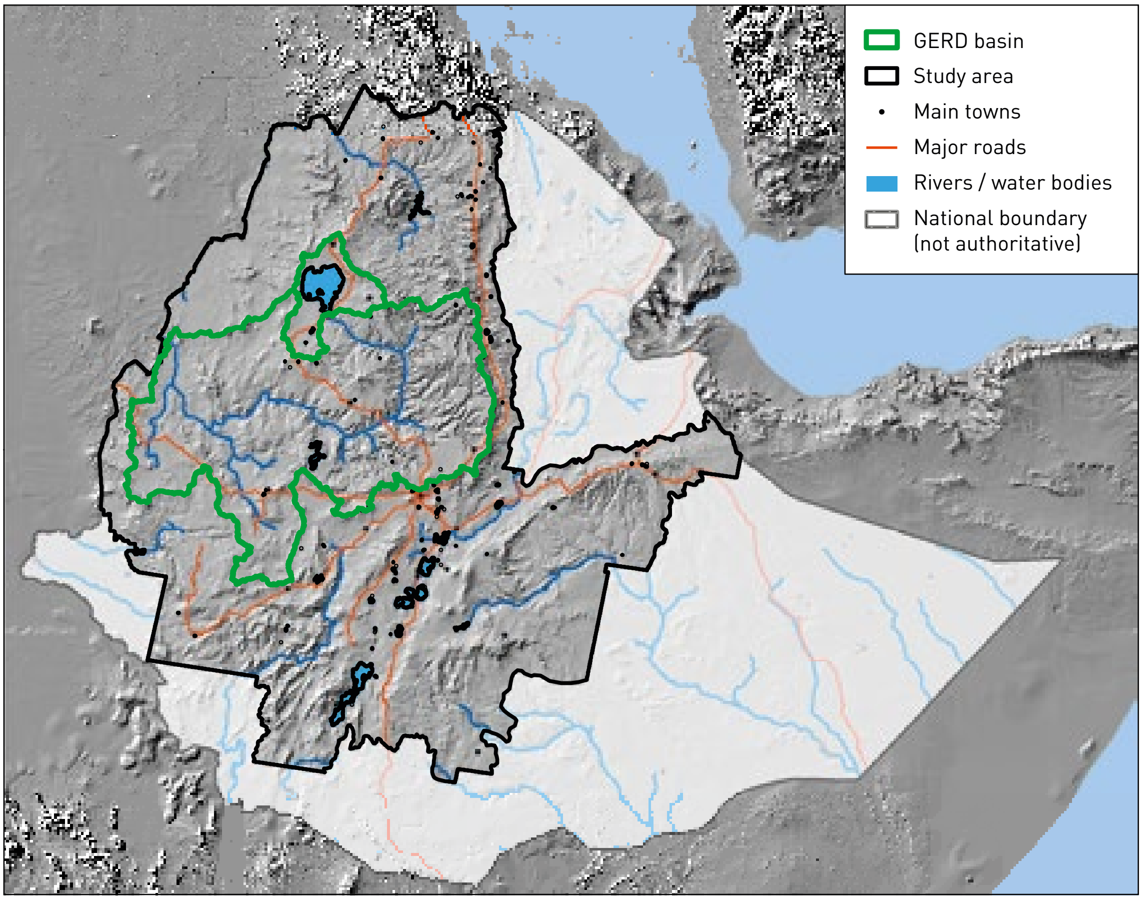
Given the calibration sites being rather small in comparison to the area where it was planned to apply the extrapolation, not all land cover and soil types that exist in the whole study area were found within the calibration sites. These missing values were therefore btoh derived from literature and related to (similar) calibrated parameter values. Additionally, authors needed to estimate all parameter values for the agro-ecological zones where no calibration sites were available. This concerned the following zones: Dry Kolla, Moist Kolla, Wet Kolla, Dry Dega, Moist High Dega, Moist Wurch, and Wet Wurch. For these zones, USPED parameter values were derived from agro-ecological zones where calibration sites were available by considering their precipitation regime (dry, wet, moist), and altitudinal range (Kolla, Weyna Dega, Dega, High Dega, Wurch). *Table 5* shows input data and method of the parameter estimation.

Extrapolation calibration and verification

In order to assess whether the erosion/deposition estimates of the USPED model for the study area using the parameter values calibrated for the small SCRP catchments were reliable, authors verified the results for the basin of the Grand Ethiopian Renaissance Dam (GERD; Abbay River Basin, see *Figure 20*).

FIGURE 20

The GERD basin (Abbay river), including the delineation of the contributing Lake Tana sub-basin



This basin covers an area of 174,494 km^2 and is said to have a sediment yield at the location of the GERD of at least 300 million tonnes/yr. Abdelsalam (2008) compiled data and information on sediment in the Nile River system and presented a figure of 285 million tonnes/yr for the proposed Mandaya Hydropower Dam, which is to be located about 200 km upstream of GERD and has a catchment of 128,729 km^2. Unfortunately the date and methodology of measuring the sediment yield is unknown to authors, who also do not know how much of the sediments for the Lake Tana sub-basin remain in Lake Tana. Alternative data on sediment yields for larger catchments was also not available or found to be unsuitable. For example, data from the Hydrological Stations of the Ministry of Water Resources show long term measurements (30 years), but less than ten measurements per year, which is not sufficient to derive annual sediment yields. At the very least, daily sampling and sampling during extreme events is required to assess sediment yields.

After running the USPED model for the study area and calculating the sediment yield for the GERD basin, authors found that the parameter calibration provided too high of a sediment yield, even if the parameters were set at quite low values. This meant the further reduction of parameter values in order to obtain the targeted sediment yield. As already discussed, the model mostly uses the same parameters as the USLE. However, when applied in the USPED, most of these parameters showed lower values than when applied in the USLE, especially the C- and P-factors. Therefore, the R-factor was further reduced by 7 per cent, and the K-factor by 10 per cent. This provided a total sediment yield at the location of the GERD of approximately 319 million tonnes/yr, or, assuming that one third of the sediment yield of Lake Tana sub-basin remains in Lake Tana, a sediment yield of approximately 308.6 million tonnes/yr. This result was deemed suitable and thus parameter values did not need further calibration. Information on each parameter value for the different agro-ecological zones is provided in *Table 6*.

Erosion/deposition estimates for Scenario 3.1, 3.2, 4.1, and 4.2

As mentioned previously, this study looked at different scenarios, some of which consider the conservation of all croplands with slopes > 8 per cent. As these conservation structures will change erosion/deposition rates, the USPED model needed to be run with an adapted P-factor. For this calculation, a P-factor of 0.4 was again assumed, but this time for all croplands with slopes > 8 per cent in addition to the existing structures. Besides the P-factor no adaptions were made to the other parameter values. Results of this calculation and the comparison with the previous erosion/deposition estimates are provided in the following section.

Correction of erosion/deposition rates

Looking at the erosion/deposition rates which individual pixels provide, it was found that a small share of pixels showed unrealistically high erosion/deposition rates (> 75 tonnes/pixel (> 830 tonnes/ha)). Specifically, this concerned approximately 0.12 per cent of the erosion pixels and 0.08 per cent of the deposition pixels for Scenario 1.1, 1.2, 2.1, and 2.2, and 0.09 per cent of the erosion pixels and 0.06 per cent of the deposition pixels for Scenario 3.1, 3.2, 4.1, and 4.2. Such high erosion rates have never been observed when looking at long time series of plot measurements in the Ethiopian Highlands.

Looking at the spatial distribution of these pixels, authors found the following reasons for these unrealistically high estimates: First, high erosion/deposition rates cluster: when high erosion occurs upslope, there is high deposition downslope (high sediment transport capacity on steep slopes upslope results in high erosion and then, due to the reduced sediment transporting capacity on the downslope moderate slopes, high depositions are modelled). Second, high erosion rates occur in areas with steep to very steep slopes. In these areas, it is likely that the land cover is actually bare rock (steep cliffs). However, due to Landsat data resolution, these cliffs cannot be detected when classifying the data. If these cliffs are surrounded by cropland, for example, they will also be mapped as such. The wrongly assigned C-factor, in combination with the steep slope, will then result in very high erosion rates (and deposition downslope), which does not represent reality.

Based on these findings, it was therefore decided to lower the erosion/deposition rates of these pixels to 75 tonnes per pixel (830 tonnes/ha). This adaption was necessary, as authors planned to calculate future crop production from soil depth. These high erosion/deposition rates would affect future soil

TABLE 6

Parameter calibration of the USPED model targeting a sediment yield of 300 million tonnes/yr at the GERD
*(In red: parameter values from the calibration sites, in **black**: estimated parameter values)*

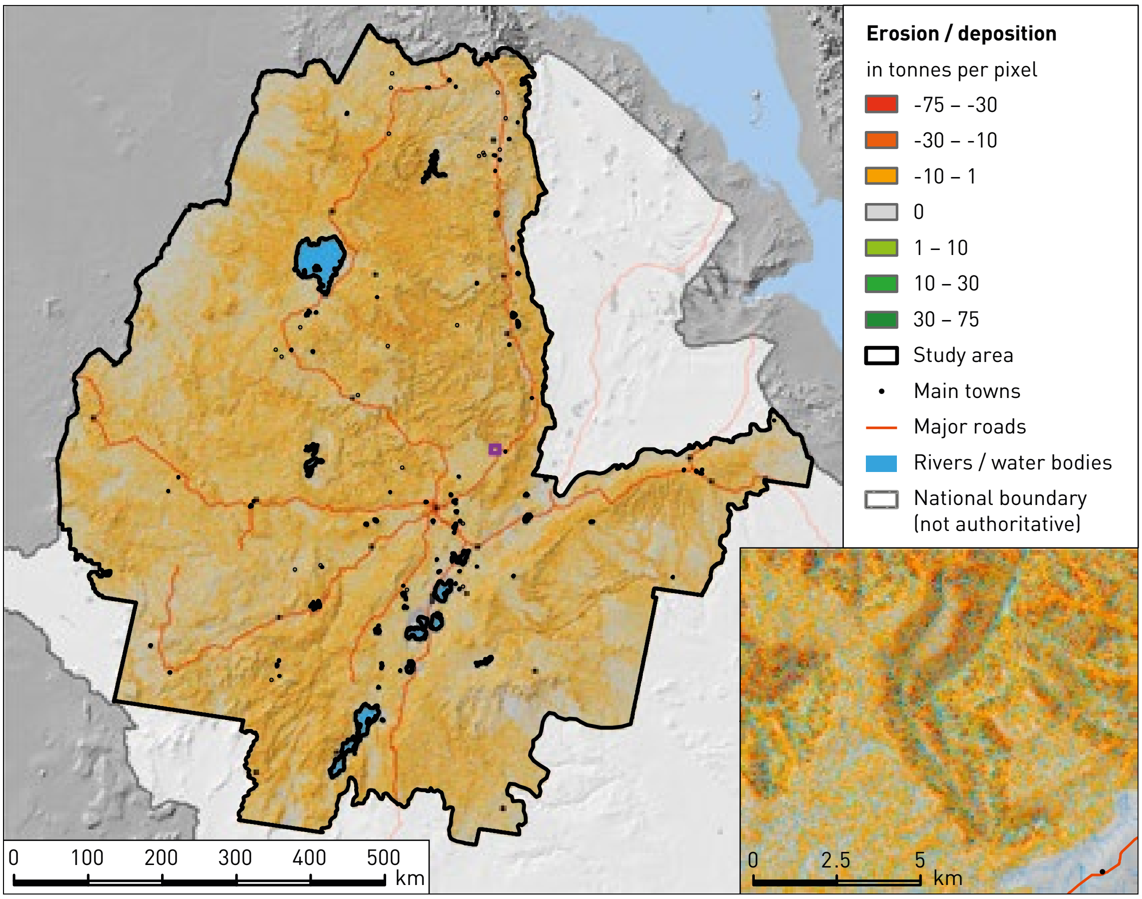
	Dry Kolla	Moist Kolla	Wet Kolla	Dry Weyna Dega	Moist Weyna Dega	Wet Weyna Dega	Dry Dega	Moist Dega	Wet Dega	Moist High Dega	Wet High Dega	Moist Wurch	Wet Wurch
Land Cover	**C-factors**												
Water body	0	0	0	0	0	0	0	0	0	0	0	0	0
Settlement	0	0	0	0	0	0	0	0	0	0	0	0	0
Forest	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
High forest	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Dryland forest	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Woodland	0.07	0.07	0.06	0.07	0.07	0.06	0.07	0.07	0.03	0.05	0.03	0.05	0.03
Shrub and bush	0.07	0.07	0.06	0.07	0.07	0.06	0.07	0.07	0.03	0.05	0.03	0.05	0.03
Riverine vegetation	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Afro-alpine vegetation	0.05	0.05	0.04	0.05	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Church forest	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Homestead plantation	0.08	0.08	0.04	0.08	0.07	0.04	0.07	0.07	0.05	0.06	0.05	0.06	0.05
Agroforestry	0.06	0.06	0.04	0.06	0.06	0.04	0.06	0.06	0.04	0.05	0.04	0.05	0.04
Grassland (drained)	0.05	0.05	0.04	0.05	0.05	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.04
Grassland (wet/un-drained)	0.04	0.04	0.03	0.04	0.04	0.03	0.04	0.04	0.03	0.03	0.03	0.03	0.03
Savanna grassland	0.05	0.05	0.04	0.05	0.05	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.04
Wetland	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Seasonal flooded area	0.04	0.04	0.03	0.04	0.04	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Cropland with trees	0.11	0.11	0.08	0.11	0.09	0.08	0.1	0.09	0.08	0.08	0.08	0.08	0.08
Cropland	0.13	0.13	0.09	0.13	0.1	0.09	0.11	0.1	0.09	0.09	0.09	0.09	0.09
Cropland in hilly terrain	0.13	0.13	0.09	0.13	0.1	0.09	0.11	0.1	0.09	0.09	0.09	0.09	0.09

	Dry Kolla	Moist Kolla	Wet Kolla	Dry Weyna Dega	Moist Weyna Dega	Wet Weyna Dega	Dry Dega	Moist Dega	Wet Dega	Moist High Dega	Wet High Dega	Moist Wurch	Wet Wurch
Land Cover (cont.)							**C-factors**						
Irrigated fields	0.13	0.13	0.09	0.13	0.1	0.09	0.11	0.1	0.09	0.09	0.09	0.09	0.09
Bare land	0.15	0.15	0.13	0.15	0.15	0.13	0.15	0.15	0.13	0.14	0.13	0.14	0.13
Degraded hills	0.15	0.15	0.13	0.15	0.15	0.13	0.15	0.15	0.13	0.14	0.13	0.14	0.13
Exposed rock	0	0	0	0	0	0	0	0	0	0	0	0	0
River course	0	0	0	0	0	0	0	0	0	0	0	0	0
Plantation forest	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Large scale investment	0.13	0.13	0.09	0.13	0.1	0.09	0.11	0.1	0.09	0.09	0.09	0.09	0.09
Mining site	0	0	0	0	0	0	0	0	0	0	0	0	0
Woodland open	0.08	0.08	0.05	0.08	0.04	0.05	0.06	0.04	0.03	0.03	0.03	0.03	0.03
Woodland dense	0.06	0.06	0.04	0.06	0.03	0.04	0.04	0.03	0.02	0.02	0.02	0.02	0.02
Shrub and bush open	0.08	0.08	0.05	0.08	0.04	0.05	0.06	0.04	0.03	0.03	0.03	0.03	0.03
Shrub and bush dense	0.06	0.06	0.04	0.06	0.03	0.04	0.04	0.03	0.02	0.02	0.02	0.02	0.02
Afro-alpine vegetation (bush and shrub)	0.06	0.06	0.05	0.06	0.05	0.05	0.05	0.05	0.03	0.04	0.03	0.04	0.03
Afro-alpine vegetation (grassland)	0.05	0.05	0.04	0.05	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03
Agroforestry, enset	0.06	0.06	0.04	0.06	0.05	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.04
Agroforestry, chat and cereals	0.06	0.06	0.04	0.06	0.05	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.04
Agroforestry, enset and chat	0.06	0.06	0.04	0.06	0.05	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.04
Agroforestry, coffee	0.06	0.06	0.04	0.06	0.05	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.04
Agroforestry, inset and coffee	0.06	0.06	0.04	0.06	0.05	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.04
Agroforestry, banana	0.06	0.06	0.04	0.06	0.05	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.04
Agroforestry, banana and mango	0.06	0.06	0.04	0.06	0.05	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.04
Agroforestry, inset, banana, and mango	0.06	0.06	0.04	0.06	0.05	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.04
Swamp	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Shifting cultivation	0.08	0.08	0.05	0.08	0.07	0.05	0.07	0.07	0.05	0.06	0.05	0.06	0.05

	Dry Kolla	Moist Kolla	Wet Kolla	Dry Weyna Dega	Moist Weyna Dega	Wet Weyna Dega	Dry Dega	Moist Dega	Wet Dega	Moist High Dega	Wet High Dega	Moist Wurch	Wet Wurch
Soil Types	**K factors**												
Alisols	0.225	0.225	0.207	0.225	0.225	0.207	0.225	0.225	0.225	0.225	0.225	0.225	0.225
Andosols	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Arenosols	0.225	0.225	0.207	0.225	0.225	0.207	0.225	0.225	0.225	0.225	0.225	0.225	0.225
Chernozems	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Calcisols	0.225	0.225	0.207	0.225	0.225	0.207	0.225	0.225	0.225	0.225	0.225	0.225	0.225
Cambisols	0.108	0.108	0.09	0.108	0.09	0.09	0.099	0.09	0.09	0.09	0.09	0.09	0.09
Fluvisols	0.126	0.126	0.099	0.126	0.108	0.099	0.117	0.108	0.108	0.108	0.108	0.108	0.108
Gypsisols	0.225	0.225	0.207	0.225	0.225	0.207	0.225	0.225	0.225	0.225	0.225	0.225	0.225
Leptosols	0.108	0.108	0.09	0.108	0.09	0.09	0.099	0.09	0.09	0.09	0.09	0.09	0.09
Luvisols	0.162	0.162	0.117	0.162	0.135	0.117	0.144	0.135	0.135	0.135	0.135	0.135	0.135
Lixisols	0.153	0.153	0.117	0.153	0.135	0.117	0.144	0.135	0.135	0.135	0.135	0.135	0.135
Nitisols	0.153	0.153	0.108	0.153	0.135	0.108	0.144	0.135	0.135	0.135	0.135	0.135	0.135
Phaeozems	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Regosols	0.126	0.126	0.099	0.126	0.108	0.099	0.117	0.108	0.108	0.108	0.108	0.108	0.108
Solonchaks	0.153	0.153	0.117	0.153	0.135	0.117	0.144	0.135	0.135	0.135	0.135	0.135	0.135
Solonetz	0.225	0.225	0.207	0.225	0.225	0.207	0.225	0.225	0.225	0.225	0.225	0.225	0.225
Vertisols	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Not defined	0.153	0.153	0.108	0.153	0.135	0.108	0.144	0.135	0.135	0.135	0.135	0.135	0.135
	R-factor												
Precipitation	(Precipitation * 0.3602 + 47.568) * 0.9												
	P-factor												
Conservation structure distribution	0.4 when conserved with structures, otherwise 1												

FIGURE 21

Estimated net erosion/deposition from the USPED model for the study area and for a detailed extent around the town of Debre Birhan



depth unrealistically (and thus the development of crop production) and needed to be corrected.

2.3.4 USPED model results and discussion

The erosion/deposition estimates of the USPED model at pixel level allowed for the extraction of information on the erosion/deposition rates for specific locations (pixel resolution), but also for the summary of a given unit (e.g., catchments, watersheds, larger basins, or administrative units) within the study area. *Figure 21* shows the erosion/deposition rates for the study area, as well as the level of detail for the extraction of information for specific locations.

Having applied the USPED model in two versions, one assuming the current distribution of conservation structures (Scenarios 1.1, 1.2, 2.1, and 2.2) and the other assuming that all croplands with slopes >8 per cent are conserved (Scenarios 3.1, 3.2, 4.1, and 4.2), authors could assess how further construction of conservation structures would affect net erosion/deposition rates, for specific locations or any given unit. Besides the further use within this project (using the two different net erosion/deposition rates to estimate future crop production from resulting soil depths), it also allows for the assessment of how the conservation structures will change the sediment load in rivers. This is crucial, for example, in the estimation of siltation rates in reservoirs.

However, when interpreting results and applying them for decision-making, one needs to be aware of two main limitations:

1. While information at pixel level is available, a single pixel may not provide the full 'truth'. This is related to inaccuracies of the input data for individual pixels and mainly concerns the P-fac-

tor/model of the current conservation structure distribution. As these structures were modelled using proxies as described in *Chapter 2.2.2* and not mapped from remote sensing imagery/field surveys, the distribution of structures in reality can differ from the modelled ones at pixel level.

2. The USPED model was calibrated targeting the 300 million tonnes/yr of sediment yield specified for the GERD, as derived from Abdelsalam (2008). Any interpretation of the results therefore needs to consider this calibration, and that authors do not know how and when this specified sediment yield measured.

Despite these limitations, the erosion/deposition estimates obtained from the USPED model provide good information on soil erosion and how further construction of conservation structures on the cropland will affect the erosion/deposition – at country, subunit, and even pixel level. *Table 7* shows the sum of the erosion and deposition for different analysis units.

Based on the net erosion/deposition estimates of the USPED model, annual net erosion/deposition for the extent of the study area is 940,893,165 tonnes, or 18 tonnes/ha. This estimate considers the conservation structures that currently exist in the

TABLE 7

Sum of the modelled net erosion/deposition rates per year for different units within the study area

	Version 1 Current distribution of conservation structures (Scenarios 1.1, 1.2, 2.1, 2.2)	Version 2 All croplands with slopes › 8% conserved (Scenarios 3.1, 3.2, 4.1, 4.2)	Per cent change between Version 1 and Version 2
Sum of net erosion/deposition for the study area (in tonnes)	−940,893,165	−763,061,164	−18.9
Sum of net erosion/deposition for the cropland area (in tonnes)	−379,255,511	−221,704,312	−41.5
Sum of net erosion/deposition for the GERD basin (in tonnes)	−319,010,900	−250,934,400	−21.3
Sum of net erosion/deposition for the cropland in the GERD basin (in tonnes)	−143,461,060	−82,011,370	−42.8
Sum of net erosion/deposition within different slope classes (in tonnes); area of the slope class in brackets			
0–2 % (31,342 km²)	17,554,600	15,147,100	−14.0
2–5 % (49,482 km²)	6,702,490	4,486,350	−33.0
5–8 % (59,008 km²)	−153,863	−4,378,670	2,746 (!)
8–16 % (130,123 km²)	−74,650,700	− 50,196,300	−33.0
16-30 % (126,505 km²)	−240,861,000	−164,951,000	−32.0
30–45 % (66,619 km²)	−231,512,000	−191,248,000	−17.0
› 45 % (59,006 km²)	−417,972,000	−371,921,000	−11.0
Sum of net erosion/deposition for the cropland within different slope classes (in tonnes); area of cropland within the slope class in brackets			
0–2 % (12,193 km²)	8,668,470	6,814,920	−21.0
2–5 % (20,425 km²)	2,613,030	874,189	−67.0
5–8 % (24,504 km²)	−2,261,070	−5,522,500	144.0 (!)
8–16 % (53,432 km²)	−49,033,800	−23,685,800	−52.0
16–30 % (46,366 km²)	−133,039,000	−63,132,100	−53.0
30–45 % (18,816 km²)	−88,017,900	−54,808,800	−38.0
› 45 % (11,774 km²)	−118,184,000	−82,243,100	−30.0

study area (mostly established on croplands, and in parts of Tigray and Wello also on degraded hills, grassland, shrub, and bushland). When looking at only the cropland area considered in the USPED model, 3,354,393 ha out of 18,751,262 ha of cropland are currently conserved (17.9 per cent). However, 76.5 per cent of the croplands considered in the study area show slopes > 8 per cent. In order to also conserve these areas, conservation structures need to be built on an additional 58.6 per cent of the cropland (122,077,141 ha). This was considered in Version 2 of the erosion/deposition model, and assumed that all croplands with slopes > 8 per cent are conserved. In this case, annual net erosion/deposition could be reduced to 763,061,164 tonnes, or 14.6 tonnes/ha (including the existing structures in parts of Tigray and Wello outside of the cropland). This would mean a reduction of the annual net soil erosion by 4 tonnes/ha.

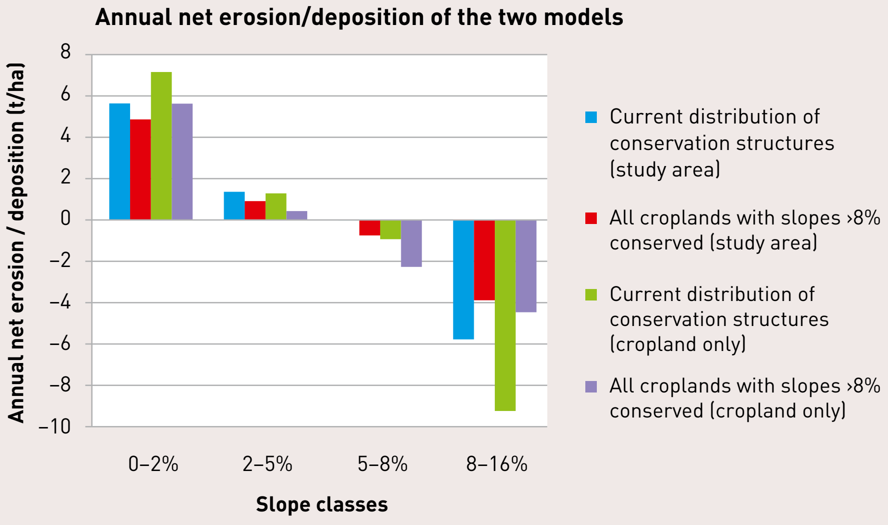
Only looking at net erosion/deposition on cropland, currently an annual net erosion/deposition of –379,255,511 tonnes (–20.2 tonnes/ha) is observed, which could be reduced to –221,704,312 tonnes (–11.8 tonnes/ha). This reduction of the erosion by 41.5 per cent (8.4 tonnes/ha) would have a positive effect, as every year 0.84 mm of topsoil would remain on the fields instead of being washed away. The situation in the GERD basin looks similar to the whole study area: the additional structures on cropland with slopes > 8 per cent could reduce overall net erosion from all land cover classes by 21.3 per cent, and even by 42.8 per cent when only considering cropland. In absolute values this would mean a reduction from –319,010,900 tonnes/yr to –250,934,400 tonnes/yr. However, one needs to consider that the USPED model was calibrated to approximately deliver the 300 million tonnes of sediment yield estimated for the GERD even though it is not actually known how and when this figure was measured/ estimated (Abdelsalam 2008).

When looking at the modelled erosion/deposition rates for the different slope classes, a clear pattern can be observed (see *Figure 22*): slopes of 0–5 per cent show deposition, while slopes > 5 per cent show erosion, whether being conserved with structures or not. When comparing the two versions (current conservation, and conservation of croplands with slopes > 8 per cent), an interesting effect

FIGURE 22

Annual net erosion/deposition for different units (complete study area and cropland only) and the two models (current distribution of conservation structures and all croplands with slopes › 8 per cent conserved)

(To make the comparably small net erosion/deposition values of the slope classes 2–5 per cent and 5–8 per cent visible, erosion rates of slopes › 16 per cent are not displayed)



of further construction of conservation structures can be observed: the areas with slopes of 0–5 per cent still show a lower net deposition; slopes between 5–8 per cent reveal a huge increase in the erosion, and slopes > 8 per cent show a lower erosion (due to the conservation structures). It is important to note that slopes between 5–8 per cent do not directly have more erosion: similar to slopes of 0–5 per cent, they just have less deposition, resulting in a more negative net erosion/deposition.

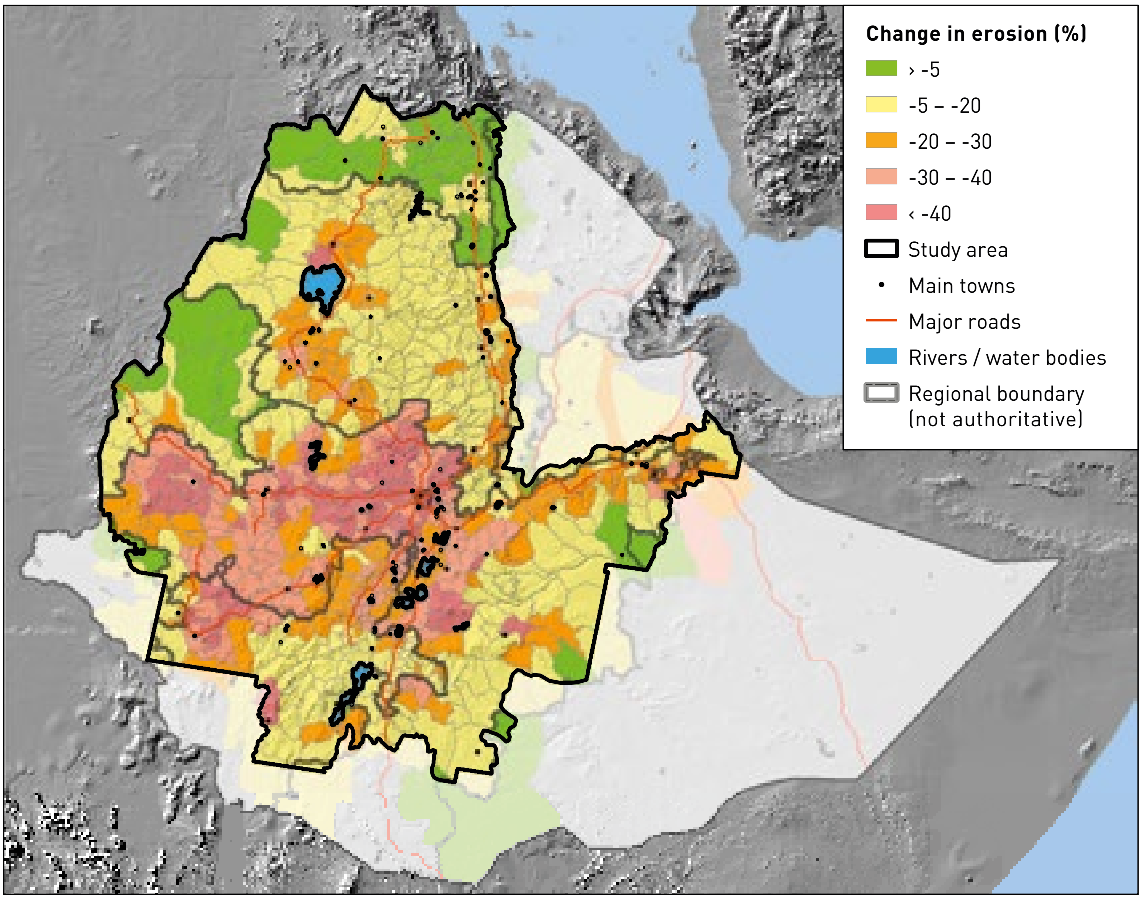
The reason for this is their location. These areas reside between flat areas and steeper hillsides. Without the steep hillsides being conserved (Version 1 of the erosion/deposition model), a lot of eroded material flows onto these areas. With the sediment transporting capacity of the water being reduced due to slope reduction, soil material is deposited. With the steep hillsides being conserved (Version 2 of the erosion/deposition model), less eroded material flows onto these areas, and despite reduced sediment transporting capacity due to slope decrease, not much material is available for deposition. As a result these areas mainly witness erosion (likely at a similar magnitude as before), but much less deposition, lowering the net erosion/deposition rate.

While the whole study area shows a change in 2,746 per cent (!) for slopes between 5–8 per cent between Version 1 and 2 of the erosion/deposition model, net erosion/deposition for these slopes shows a change of 144 per cent when considering cropland only. Also, on the cropland within this slope class, even higher net erosion/deposition can be observed

FIGURE 23

Change in erosion rates (summarized at wereda level) when constructing additional conservation structures on all croplands with slopes › 8 per cent

(With the construction of additional conservation structures there is still erosion [soil loss], but at a reduced rate as indicated in the map [e.g., orange areas: 20–30 per cent less erosion])



than in the whole study area. This big difference in the erosion/deposition rates relates to land cover: generally, cropland shows more erosion (and less deposition) than, for example, grasslands, bushlands, or forests. Without upslope conservation (Version 1), there is thus not so much deposition on cropland when compared to other land covers, which show a lot of deposition. With upslope conservation (Version 2), the situation for cropland does not change that much, but with less sediment being transported onto the other land covers, there is less deposition, which results in a much lower net erosion/deposition.

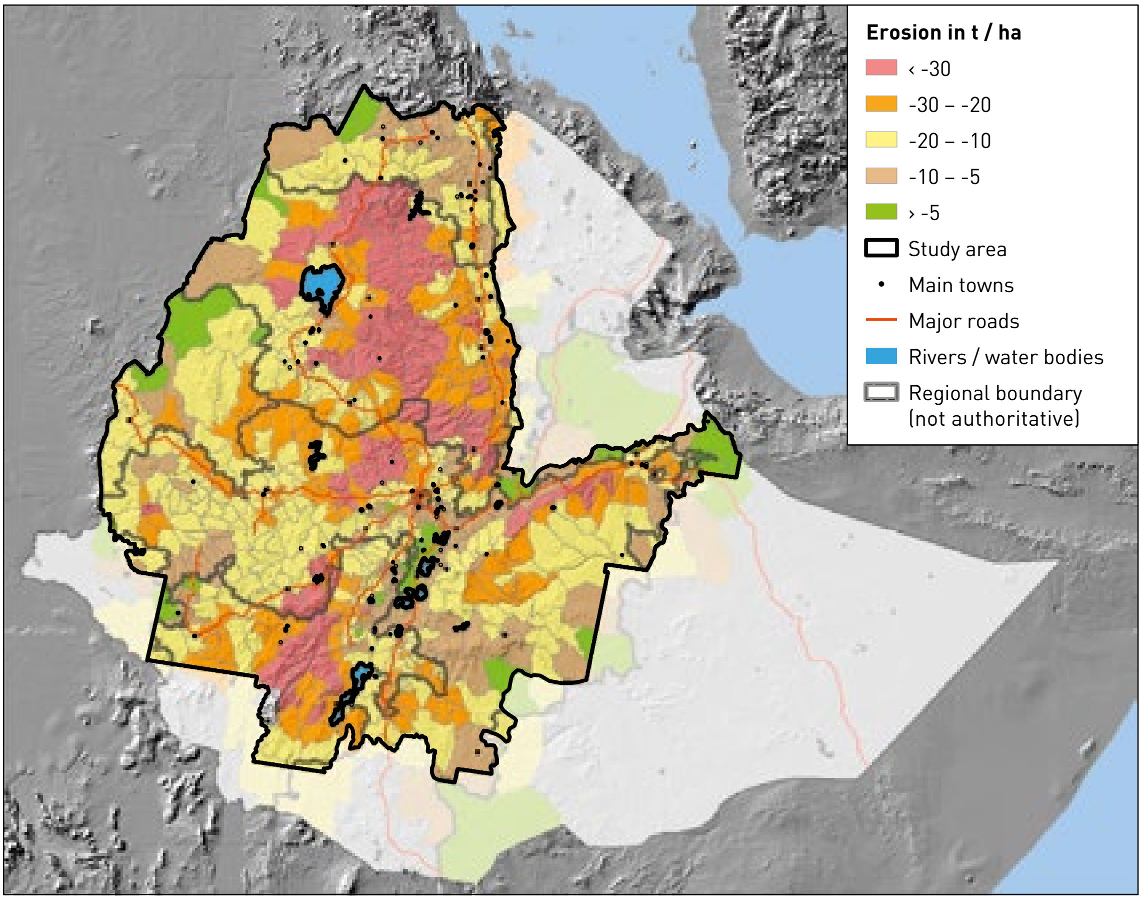
The construction of conservation structures on slopes > 8 per cent within cropland has thus a two-sided effect. On one hand, overall net erosion for the study area is reduced and erosion rates on the conserved cropland are heavily reduced. On the other hand, erosion rates on the gentle sloping land (5–8 percent) increase, especially on the cropland, as there is less deposition in these areas. In the long run it seems therefore beneficial to also conserve the gently sloping croplands below 8 per cent gradients.

To assess which weredas could show the biggest reduction in soil erosion by building conservation structures on slopes > 8 per cent where no conservation structures exist, authors calculated the per cent change in erosion rates between Version 1 and 2 of the erosion/deposition estimates. *Figure 23* shows the distribution of change in erosion rates.

In relation to the findings presented in *Table 7*, *Figure 23* clearly shows that despite the increase in erosion rates on gentle slopes when constructing con-

FIGURE 24

Net erosion/deposition in tonnes per hectare (summarized per wereda) considering the current distribution of conservation structures
(Note that all area averages are negative [net erosion])



servation structures on all croplands with slopes > 8 per cent, all the weredas still show a reduction in net erosion/deposition.

The pattern that can be observed in *Figure 23* reflects two conditions: First, the distribution of currently existing conservation structures and second, the amount of sloping cropland in the different weredas. In addition to the change in erosion rates for the targeting of focus areas for the construction of additional conservation structures on slopes > 8 per cent (cropland area), the amount of erosion within each wereda as displayed in *Figure 24* also needs to be considered.

The comparison of *Figure 23* and *Figure 24* shows that the wereda clusters with high net erosion/deposition lie mostly in different locations than clusters with high erosion change once there is construction of conservation structures on croplands with slopes > 8 per cent. The green areas in *Figure 23* show an overlap with the green and brown areas in *Figure 24*: these are low to medium erosion rates, with a small change in rates once there is construction of new structures. In all weredas of Tigray Region this is due to the large amount of conservation structures that already exists, while for the other green coloured weredas this is rather due to the small amounts of cropland on steep slopes. The yellow weredas in *Figure 23* show a reduction in the erosion rates between 5–20 per cent. While this is a medium reduction in erosion rates, the comparison with *Figure 24* shows that these areas show high erosion rates in Amhara and SNNP regions. Constructing new structures in these areas can thus be considered as beneficial.

In the Oromia region, the situation is more heterogeneous: along the eastern road leaving Addis Abeba, medium to high erosion rates and medium to high reductions of rates with the construction of additional structures overlap, making the construction of further structures beneficial. In the western part of this region, a high reduction can be achieved in areas with medium to high erosion rates, where additional structures should be built. In the south-west, new structures could also be beneficial, but are not as urgently needed as other parts of the Oromia region. In comparison to the other regions, Benishangul-Gumuz shows the lowest benefit from the construction of new structures in terms of reducing erosion. This relates to both the rather low share of cropland, and the land showing mostly no or gentle slopes. Targeting of new structures should be done on a case-by-case basis and seems to be limited to certain locations only in this region.

2.4 Component 4: Estimation of current (and future) crop production

Apart from production management, a multitude of biophysical factors contribute to the amount of crops obtained from a specific plot, with the most prominent ones being soil depth, soil type, nutrient content and fertilizer application, water availability (which relates to the amount and variability of rainfall when considering rainfed agriculture), and temperature (closely related to altitude). Numerous studies have been conducted that consider one or several of the above factors to show their effect on crop production. The studies by Belay (1992) and Ludi (2002) have shown that one of the most prominent biophysical determinants of production is soil depth. They showed that production increases with increasing soil depth, until the depths reach a threshold where further increases do not increase production (related to the maximum possible harvest of a specific crop). However, the soil depth - crop production relationships found in their studies showed weak correlation coefficients. On one hand, this related to the multitude of factors that affect crop production besides soil depth, but on the other hand, their results were also affected by a small number of samples.

Other studies (e.g., Gebremedhin et al. 1999; Gebremedhin et al. 2002; Kassie et al. 2008; Kassie et al. 2010; Kassie et al. 2011) showed that the interrelation between management options (e.g., fertilizer application, conservation structures) and water availability affect crop production. In more humid areas, the application of fertilizer allows for increased production, while in drier areas, water becomes the limiting factor and fertilizer application does not provide substantial harvest increases. In these areas, water harvesting (e.g., in the form of conservation structures) will contribute more to crop production than fertilizer application as a management option. Highest harvests can be obtained from their combination, e.g., conservation structures and fertilizer application.

The findings of these studies show a potential for the estimation of crop production using different proxies. By using this information in combination with available spatial data, authors came up with a simple crop production – soil depth relationship model by implementing the following tasks:

- Definition of crop supply baskets (See *Chapter 2.4.1*) for each agro-ecological zone;
- Definition of crop production – soil depth relationships for each agro-ecological zone/crop supply basket and for different management options (no management; fertilizer only; structures only; fertilizer and structures);
- Modelling of the distribution of current fertilizer application;
- Refinement of existing soil depth information, and;
- Calibration of the crop production – soil depth relationships for the current situation.

The following sections present the assumptions, approaches, methodologies, and datasets used to implement each of the above tasks.

2.4.1 Definition of crop supply baskets

The land cover data prepared for this study shows the location and extent of cropland, but does not provide information on the specific crop types cultivated. Without knowledge on the spatial distribution of different crop types, the estimation of crop production required the definition of the occurrence and mixture of different crops for the cropland area. Authors found the agro-ecological zones were an appropriate sub-unit for such a definition, as they divide the country into zones of homogeneous rainfall and temperature regimes. With both of these factors being major determinants for crop occurrence, the agro-ecological zones were used to define crop supply baskets. These baskets indicate the occurrence of specific crops and their respective share on the cropland area within the agro-ecological zone.

A first impression of the different crops that occur within these zones was obtained from Hurni (1998),

FIGURE 25

Crop supply baskets in High Dega agro-ecological zone (percentage of crop occurrence)

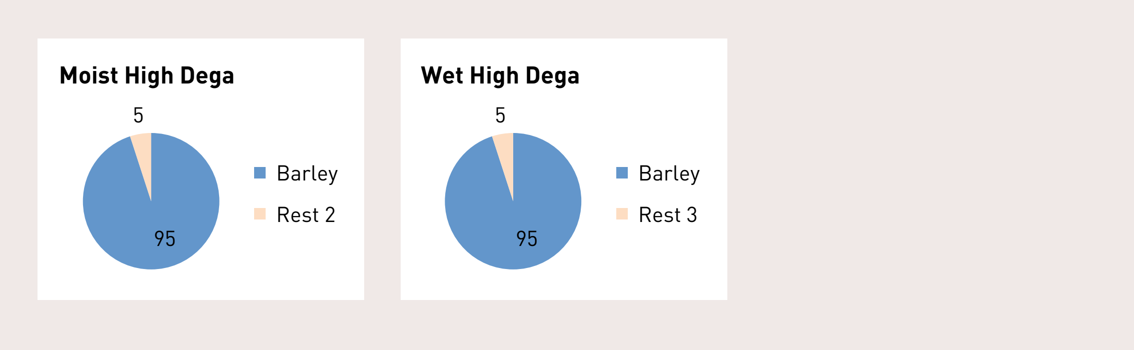


FIGURE 26

Crop supply baskets in Dega the agro-ecological zone (percentage of crop occurrence)

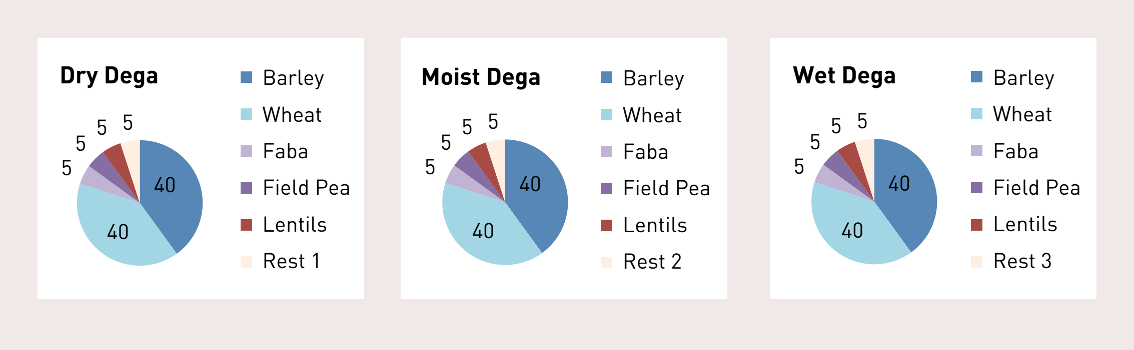


FIGURE 27

Crop supply baskets in Weyna Dega the agro-ecological zone (percentage of crop occurrence)

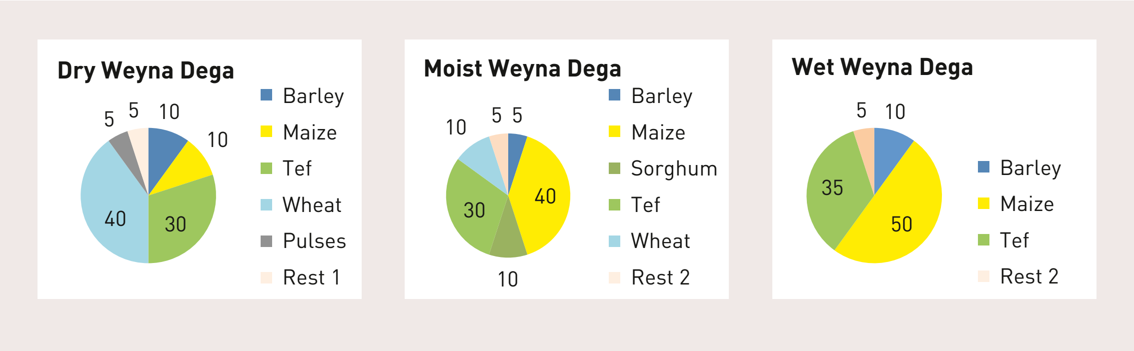
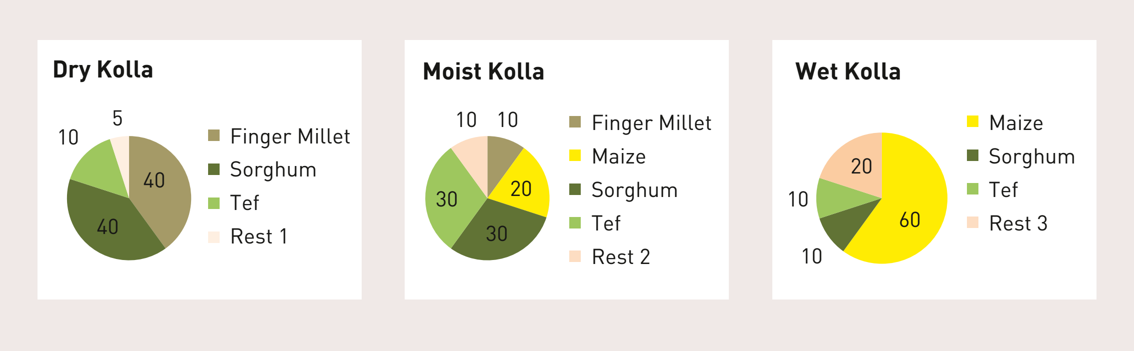


FIGURE 28

Crop supply baskets in Kolla the agro-ecological zone (percentage of crop occurrence)



see *Figure 17*. Authors then combined information from the 'Report on Area and Production of Major Crops (Agricultural Sample Survey 2012/2013)' (CSA 2013a) from the Central Statistical Authority (CSA) of Ethiopia, containing information on crop types and productivity at national, regional, and zonal level with the delineation of the agro-ecological zones. This allowed crop supply baskets to be defined for each agro-ecological zone as shown in *Figures 25–28*.

Crop types differ substantially between the different agro-ecological zones: at higher altitudes barley and wheat dominate, while at lower altitudes a mixture of crops such as barley, tef, maize, sorghum, and finger millet grow. The 'Rests' (Rest 1, Rest 2, and Rest 3) shown in *Figures 25–28* constitute a variety of crops that only occur in smaller shares within the agro-ecological zones.

This definition of the crop supply basket allowed the study to overcome the problem of only having spatial information on cropland and not crop types. It also allowed crop productivity variations due to temperature and precipitation, and how management options affect productivity, also in relation to temperature and precipitation.

2.4.2 Definition of crop production – soil depth relationships for crop supply baskets

As previous research showed, the productivity of specific crops is related to soil depth, temperature, precipitation, and management options. While other management options (e.g., minimum tillage, intercropping) exist and are known to have an impact on productivity, spatial information on these management options was not available, and therefore could not be considered in this study. Only conservation structures and fertilizer were considered as management options in the study at hand.

TABLE 8

Productivity levels of crops according to precipitation and management option
(1 stands for highest and 4 for lowest ranking)

	Dry	Moist	Wet
A) Conservation structures/fertilizer	1	1	1
B) Fertilizer only	3	2	2
C) Conservation structures only	2	3	3
D) No management	4	4	4

Considering precipitation and the management options, crop productivity is affected as shown in *Table 8*. The productivity ranking (1–4) shows which management options have the highest productivity.

In this ranking, only the dry region shows a different pattern due to water being the limiting factor: fertilizer can only increase yields substantially when conservation structures exist as they provide better water retention. Although not shown in *Table 8*, water availability also makes a difference between the productivities of the moist and the wet zones. In the wet zones, management options A and B show similar productivity levels, and options C and D show similar productivity levels. In the moist and wet zones option A is the highest, followed by options B and C (which show similar productivity levels) and option D with the lowest productivity level.

With this relative definition of productivity levels based on precipitation and management options, the study needed to further define absolute levels of productivity for each crop supply basket and management option. This was done using the combination of the agro-ecological zones and the 'Report on Area and Production of Major Crops (Agricultural Sample Survey 2012/2013)' (Hurni 1998; CSA 2013a). By relating the regional units to the agro-ecological zones with which they overlap, and by grouping crop type information according to the crop supply baskets, the absolute levels of productivity could be defined for each crop supply basket and management option.

Last but not least, crop production – soil depth relationships was defined for each crop supply basket and management options using field measurements (SCRP catchments) and the results of the studies of Belay (1992) and Ludi (2002) as references.

2.4.3 Distribution of current fertilizer application

The application of fertilizer has impact on crop productivity, and thus current fertilizer applications are included in this analysis. To properly calibrate the crop production – soil depths relationships as defined for the crop supply baskets, and for the following analyses, authors had to value different management options based on their costs and benefits. Unfortunately, there was no spatial data (pixel level) available that showed the current fertilizer applications within the study area. The only source of information that covered the whole study area was the 'Report on Farm Management Practices' from the agricultural sample survey of 2012/2013, CSA (2013b), which provided information on the area of cropland treated with UREA and DAP, and the amounts applied at the zonal level.

To transform the zonal level information available to the 30 m x 30 m pixel level that the study model requires, the following assumption was made: fertilizer is mainly applied on flat or gentle sloping croplands and on croplands with conservation structures. Fertilizer being a costly investment, it is less likely that farmers would apply it on croplands that have steep slopes because erosion rates on such lands are high, washing away the fertilizer in the absence of erosion reduction strategies on such croplands.

Fertilizer distribution was then implemented in the model in the following way: the amount of cropland treated with fertilizer for each zone was combined with pixel based slope information. The fertilizer was then redistributed within these zone-slope-cropland areas. Non-sloping croplands were to be treated with fertilizer (sloping croplands with conservation structures were also considered in this category). Then, the fertilizer was distributed onto the increasingly sloping croplands until the total area treated with fertilizer for the considered zone reached the amount indicated by the zonal information obtained from the CSA report. This resulted in the pixel based map in *Figure 29* showing the distribution of fertilizer. Within the study area, a total of 5,623,973 ha (2.7 per cent of the cropland) are treated with fertilizer.

2.4.4 Refinement of available soil depth data

Due to the estimation of crop production from soil depth, accurate information on soil depths is crucial. The best available data on soil depths was from FAO/LUPRD, indicating maximum and minimum soil depth observed for relatively small polygons (FAO 1998). This information allowed authors to use proxies to refine the existing map with more detailed, pixel level soil depth information.

The three spatial datasets used as proxies to refine the existing soil depth map were:

- Livelihood systems, which define farming systems and thus the type and intensity of land use. For example, areas where cereal-based farming systems occur were considered to show more shallow soils than the pastoralist areas;
- Soil type data was used to distinguish between soil types that are more or less susceptible to erosion. Soil depths were considered shallower in areas with soils more susceptible to erosion, and;
- Slope steepness was the factor with the highest weight; with increasing slopes, more shallow soils were assumed to occur.

Tables 9–11 show the soil depth reduction factors attributed to these three datasets. The process of defining these factors to obtain an accurate soil depth map involved several Ethiopian soil experts.

FIGURE 29

Currently fertilized croplands within the study area

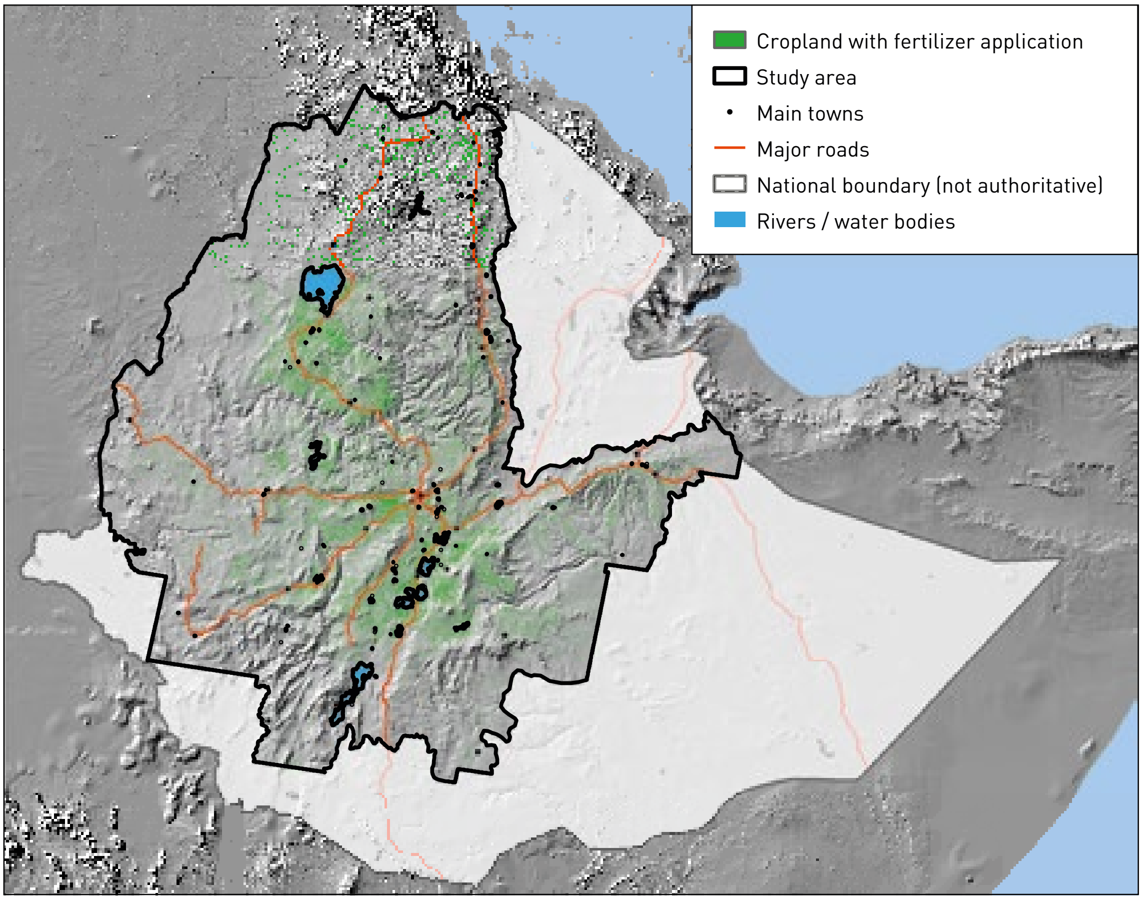


TABLE 9

Soil depth reduction factors related to the livelihood system

Livelihood system	Reduction factor
Lowland mixed – sesame livelihood system	0.975
Northern mixed midlands livelihood system	0.950
Northern cereal pulse mixed livelihood system	0.950
North West lowland sorghum/sesame mixed livelihood system	0.975
Western coffee/maize livelihood system	0.975
Southern pastoral livelihood system	1.000
Eastern highland mixed livelihood system	0.975
Awash pastoral/agricultural system	1.000
Meher/Belg transition livelihood system	0.975
North-Eastern pastoral livelihood system	1.000
Eastern chat/sorghum highland mixed livelihood system	0.975
"Ogaden" pastoral livelihood system	1.000
Highland mixed -tef livelihood system	0.950
Horticultural (enset/cereal) mixed livelihood complex	0.975
Rift Valley livelihood system	0.975
Gambella agro-pastoral livelihood system	1.000
Northern pastoral livelihood systems	1.000

TABLE 10

Soil depth reduction factor related to the susceptibility of a soil type to soil erosion

Soil type	Reduction factor
Alisols	1.00000
Andosols	0.95000
Arenosols	1.00000
Chernozems	0.95000
Calcisols	1.00000
Cambisols	0.96125
Fluvisols	0.97000
Gypsisols	1.00000
Leptosols	0.96125
Luvisols	0.97500
Lixisols	0.97500
Nitisols	0.97500
Phaeozems	0.95000
Regosols	0.97500
Solonchacks	0.97500
Solonetz	1.00000
Vertisols	0.95000

TABLE 11

Soil depth reduction factors related to the slope

(Two factors were considered, one related to the 'maximum soil depth' attribute in the FAO data [FAO 1998], and the other to the 'minimum soil depth' attribute)

Slope class	Reduction factor (max. depth)	Reduction factor (min. depth)
0–2%	1.00	0.00
2–5%	0.95	0.05
5–8%	0.90	0.10
8–16%	0.80	0.20
16–30%	0.70	0.30
30–45%	0.60	0.40
› 45%	0.50	0.50

Based on their feedback, the different factors were adapted until the quality and accuracy of the mapped soil depths was confirmed by all involved experts.

The soil depth at pixel level was calculated by first assuming that all areas with slopes of 0–2 per cent do not show shallow soils. For these areas, maximum soil depth as indicated by the FAO data was assigned. For the remaining pixels the following calculation was then performed:

$$SD = (SlpR_{max} * SD_{max} + SlpR_{min} * SD_{min}) * SR * LR$$

, where *SD* is soil depth, $SlpR_{max}$ is the slope reduction factor (maximum soil depth), $SlpR_{min}$ is the slope reduction factor (minimum soil depth), SD_{min} is the minimum soil depth, SD_{max} is the maximum soil depth, *SR* is the soil reduction factor, and *LR* is the livelihood system reduction factor.

The result of this calculation – a detailed pixel based soil depth map for Ethiopia – is shown in *Figure 30* (soil depths are displayed for the extent of the study area only).

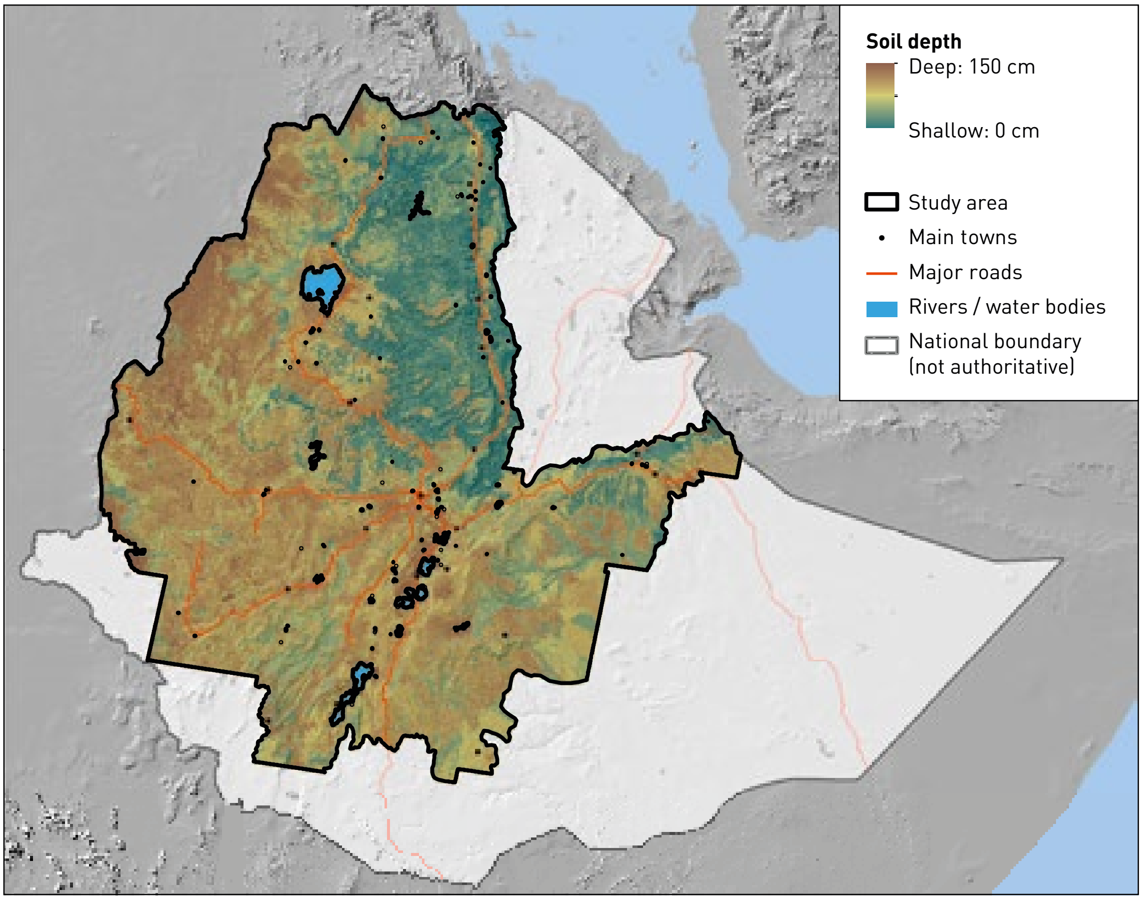
2.4.5 Calibration of crop production – soil depth relationships and calculation of crop production

The calculation of the crop production for the calibration of the crop production – soil depth relationships, defined for each agro-ecological zone, involved the following spatial parameters:

- Cropland pixels. The classes ‘cropland with trees’, ‘cropland without trees’, ‘cropland on hilly terrain’, and ‘homestead plantation’ were used. ‘Large scale investment’ was not considered, as this study considered smallholders only;
- Crop production – soil depth relationships for different management options (i.e., no technology, fertilizer only, conservation structures only, conservation structures and fertilizer) for each crop supply basket);

FIGURE 30

Pixel based current soil depth map derived from FAO data (FAO 1998) using livelihood systems, soil types, and slope as refinement proxies



- Soil depth data;
- Current fertilizer application;
- Current conservation structure distribution. Each cropland pixel has an area of 900 m^2 from which yields can be obtained. With conservation structures, this area is reduced by 1.8 m^2 per meter of conservation structure. This reduction was included in the calculation of crop production, and for each pixel with conservation structures, actual cropland area was reduced depending on the total length of conservations structures within the considered pixel, and;
- Agro-ecological zone layer.

The spatial overlap of the above layers defines the calculation of production in the following ways:

1. Cropland pixels define the areas for which yields are calculated;
2. The agro-ecological zone layer defines which crop supply basket specific crop production – soil depth relationship is applied;
3. The current fertilizer application and distribution of conservation structures define which management option specific crop production – soil depth relationship is used, and;
4. The current conservation structure distribution defines the reduction of yields due to conservation structure area loss: no reduction on cropland pixels without structures, and on cropland pixels with structures a reduction according to the amount of structures within the given pixel.

These steps resulted in a first estimate of production that could be used to calibrate the crop production – soil depth relationships for each crop supply basket and management option. As a calibration reference, crop productivities provided in the 'Report on Area and Production of Major Crops (Agricultural Sample Survey 2012/2013)' (CSA 2013a) were used. Authors calculated the amounts of production for each administrative zone based on the defined crop supply baskets (overlay of administrative zones and agro-ecological zones), crop productivities provided by the CSA, and the mapped cropland area. The crop production – soil depth relationships of the crop supply baskets and management options was then adjusted, targeting the production specified for each administrative zone while still maintaining the productivity relationships of the different management options specific for each agro-ecological zone as defined by previous research (shown in *Table 8*). These final 'calibrated' crop production – soil depth relationships for each crop supply basket/agro-ecological zone and the different management options are shown in *Figures 31–41*.

With calibrated crop production – soil depth relationships, authors could calculate crop production for the 30 year time period, as well as for the different scenarios considered in this study.

Scenarios 1.1 and 1.2 represent current fertilizer applications and distribution of conservation structures. To calculate future crop production related to these scenarios, the same input data was

FIGURE 31

Crop production – soil depth relationships for the Wet High Dega crop supply basket and management options

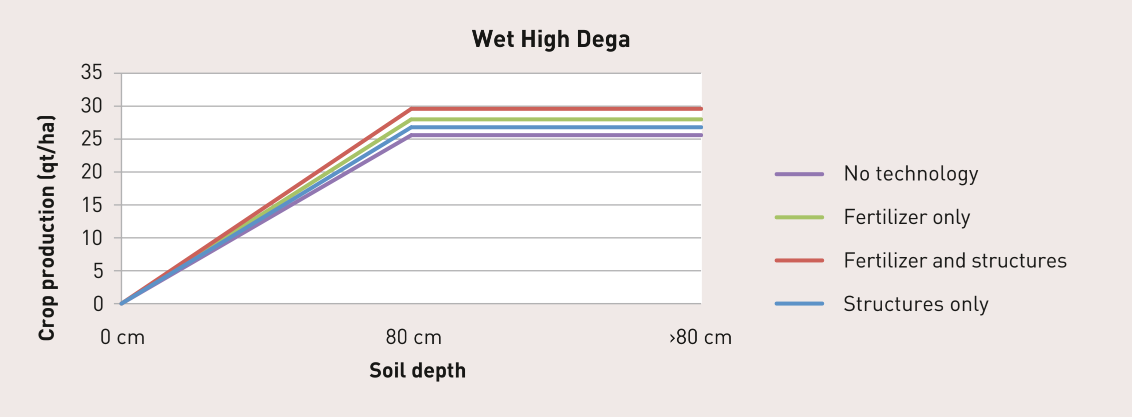


FIGURE 32

Crop production – soil depth relationships for the Moist High Dega crop supply basket and management options

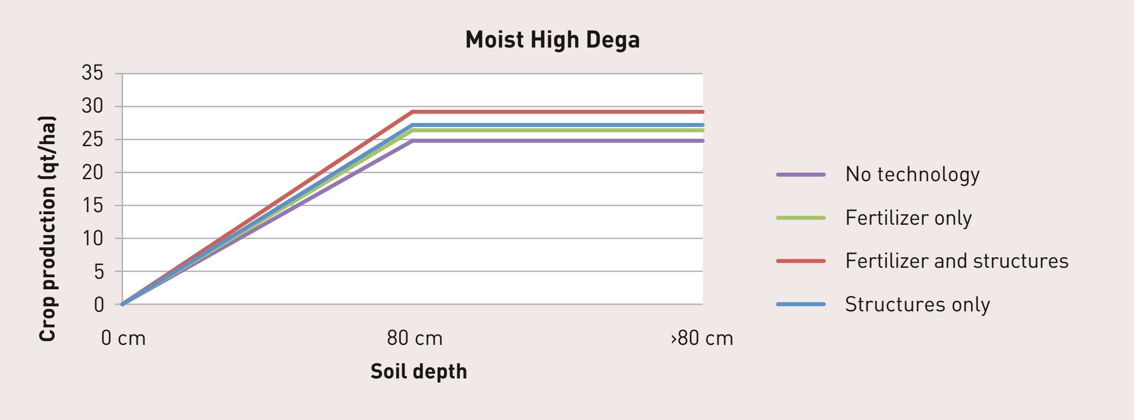


FIGURE 33

Crop production – soil depth relationships for the Wet Dega crop supply basket and management options

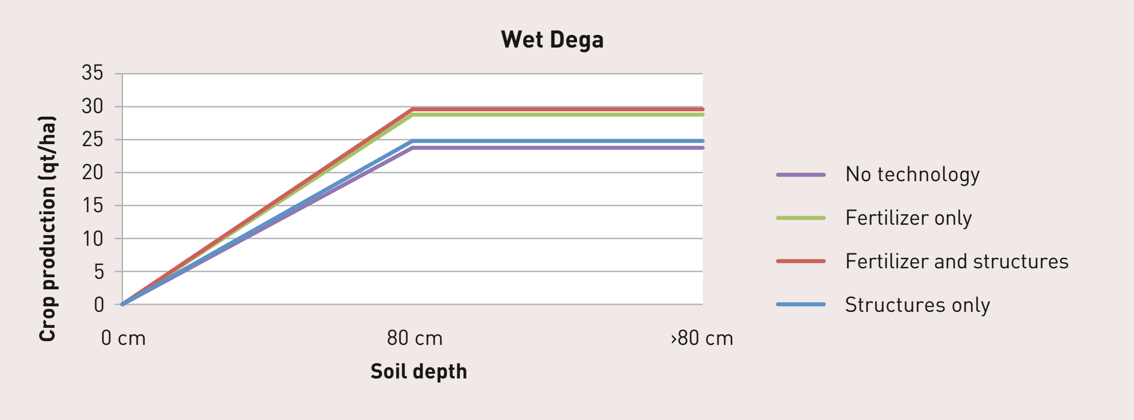


FIGURE 34

Crop production – soil depth relationships for the Moist Dega crop supply basket and management options

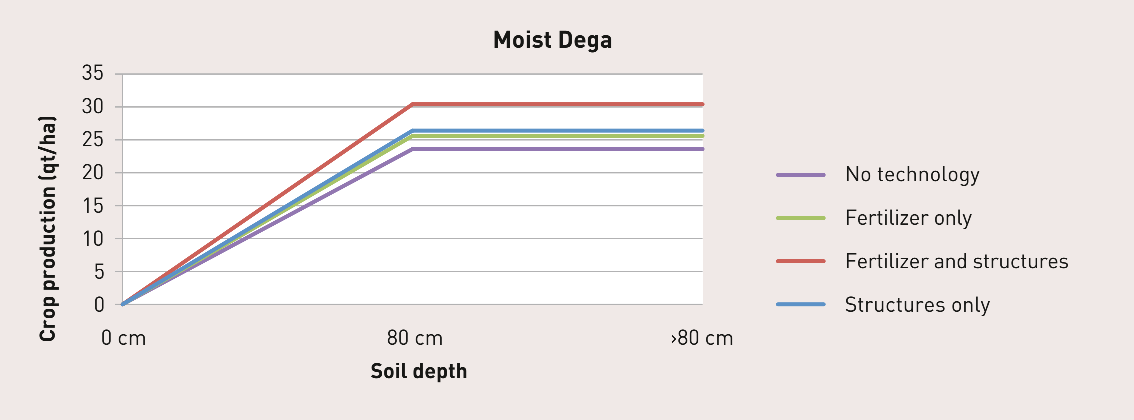


FIGURE 35

Crop production – soil depth relationships for the Dry Dega crop supply basket and management options

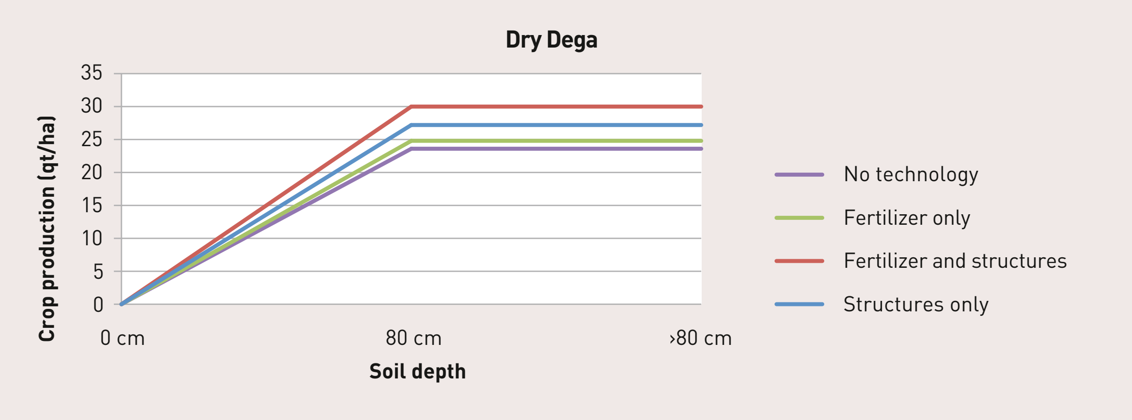


FIGURE 36

Crop production – soil depth relationships for the Wet Weyna Dega crop supply basket and management options

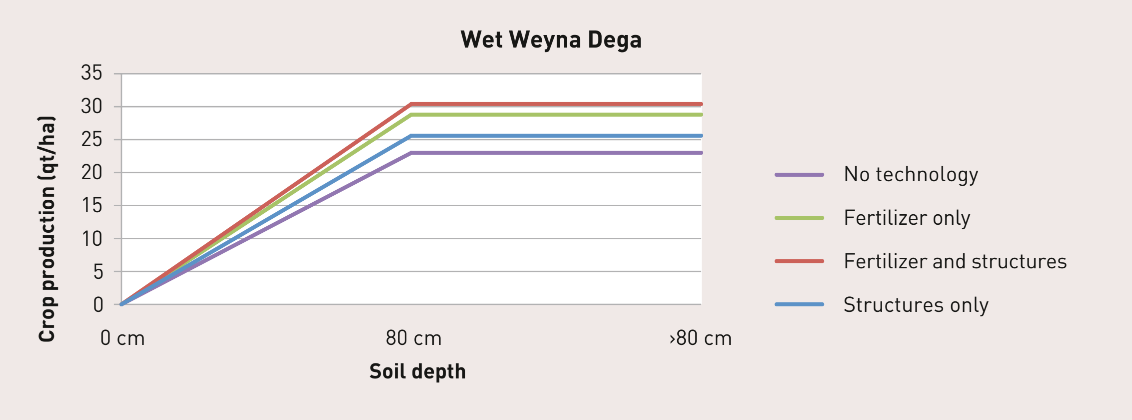


FIGURE 37

Crop production – soil depth relationships for the Moist Weyna Dega crop supply basket and management options

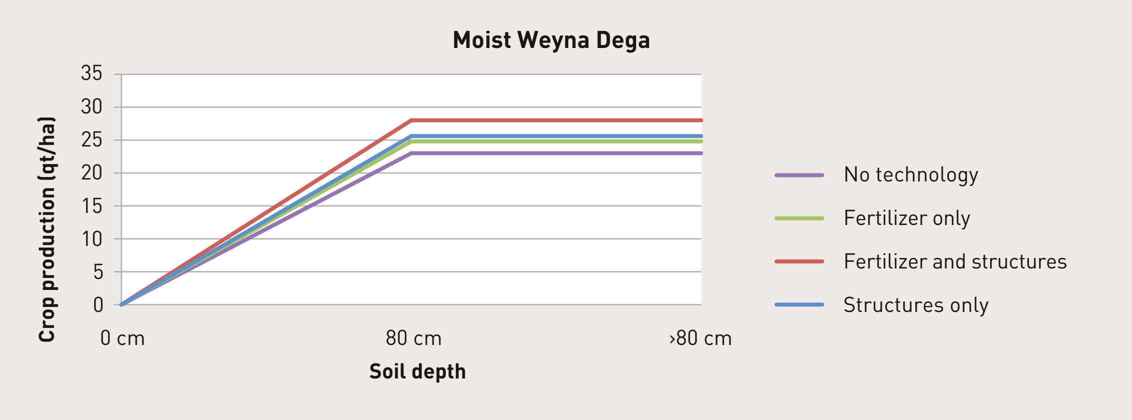


FIGURE 38

Crop production – soil depth relationships for the Dry Weyna Dega crop supply basket and management options

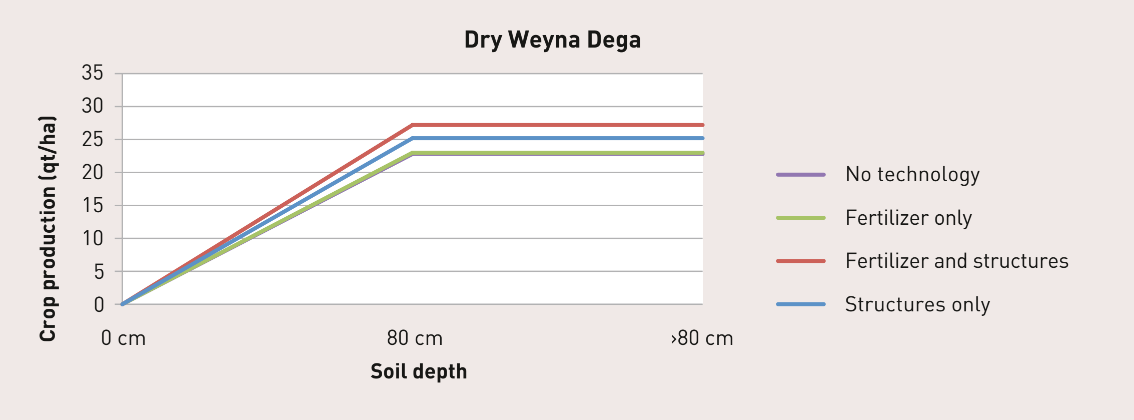


FIGURE 39

Crop production – soil depth relationships for the Wet Kolla crop supply basket and management options

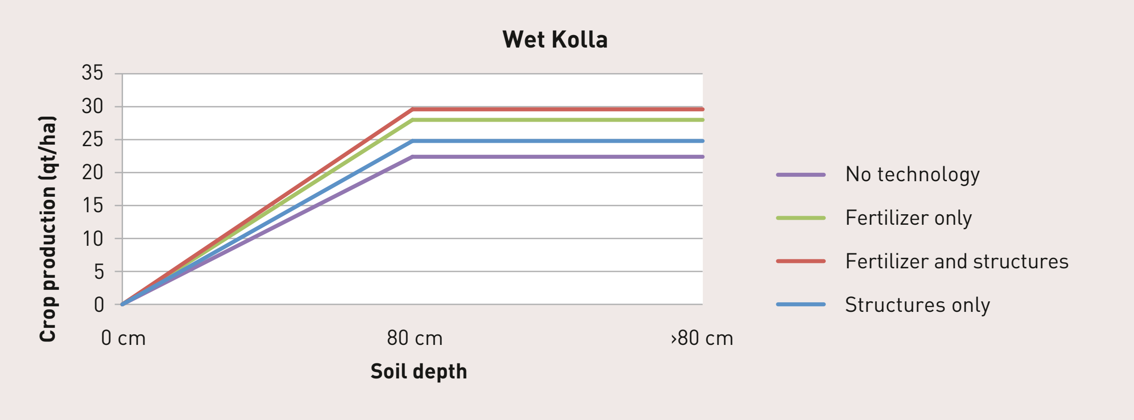


FIGURE 40

Crop production – soil depth relationships for the Moist Kolla crop supply basket and management options

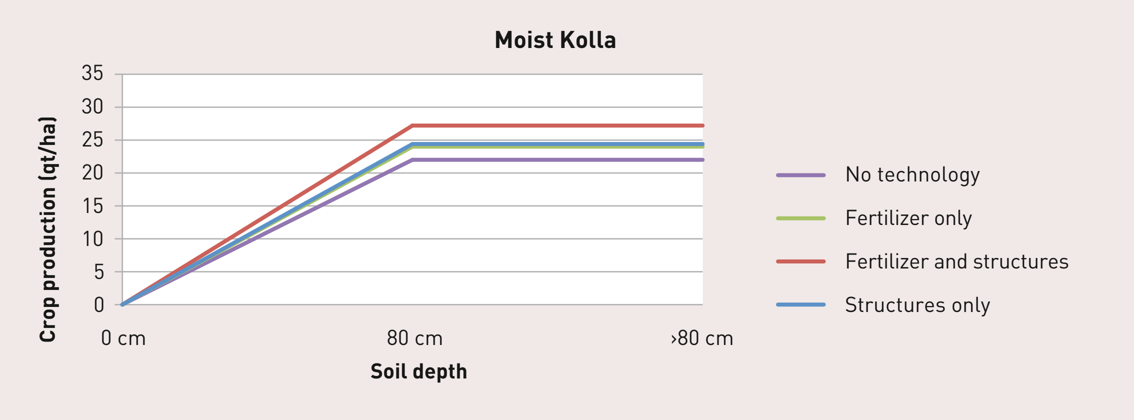


FIGURE 41

Crop production – soil depth relationships for the Dry Kolla crop supply basket and management options

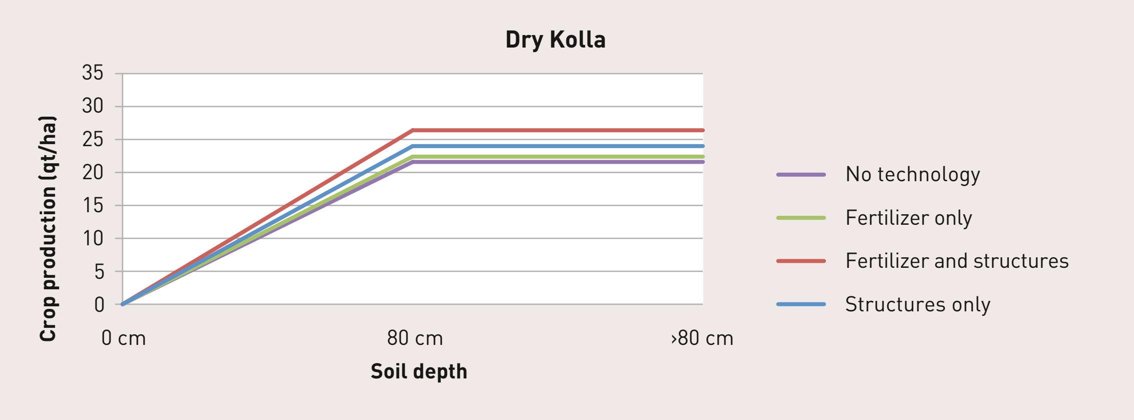


TABLE 12

Data used for computing crop production for the different scenarios (different management options)

Scenario Input layer	Scenarios 1.1, 1.2 Business as usual (current distribution of conservation structures and currently fertilized croplands)	Scenarios 2.1, 2.2 Current distribution of conservation structures, but fertilizer on all croplands	Scenarios 3.1, 3.2 Conservation structures on all croplands with slopes › 8%, currently fertilized croplands	Scenarios 4.1, 4.2 Conservation structures on all croplands with slopes › 8%, fertilizer on all croplands
Agro-ecological zones	×	×	×	×
Soil depth	×	×	×	×
Current extent of fertilizer application	×		×	
Fertilizer on all croplands		×		×
Current distribution of conservation structures	×	×		
Conservation structures on all croplands with slopes › 8%			×	×
Erosion/deposition 1 (current distribution of conservation structures)	×	×		
Erosion/deposition 2 (conservation structures on all croplands with slopes › 8%)			×	×

used as for the calibration of the crop production – soil depth relationships (see above). For Year 0, authors used the new pixel based soil depth map to derive the crop production at that time. To estimate crop production for the following 30 years, the soil depth was then consecutively reduce by the annual net amount of eroded soil or increased it by the annual net amount of deposited soil.

For the other scenarios, the calculation was performed the same, but the input layers changed depending on the considered management options. *Table 12* provides an overview of the layers included in the estimation of production according to the scenarios.

The calculation of the four scenarios allowed an assessment of how further expansion of the two management options (application of fertilizer and construction of conservation structures) affect crop production today and over the coming 30 years, and to perform a CBA of the different management options.

2.4.6 Crop production estimation results and discussion

The crop production estimation worked fairly well, considering the study used three modelled parameters (soil depth, fertilizer application, and conservation structures) out of the multitude of factors that affect crop production. *Table 13* shows the amounts of current crop production calculated using the crop productivity per hectare information from the CSA, crop production estimated by this model, and the deviation between the two for each agro-ecological zone.

As *Table 13* shows, the developed model deviates from the CSA crop production by only 0.78 per cent. This is because authors calibrated the model targeting the crop production amount as indicated by the CSA data. However, the crop yield – soil depth relationships still match the findings of previous studies on how different management options affect crop production within different agro-ecological zones. This also explains why some of the agro-ecological zones have greater deviations from the CSA data than others. Additionally, it has to be noted that the CSA data is an extrapolation from a rather small number of plot measurements and may thus deviate from reality. Without any

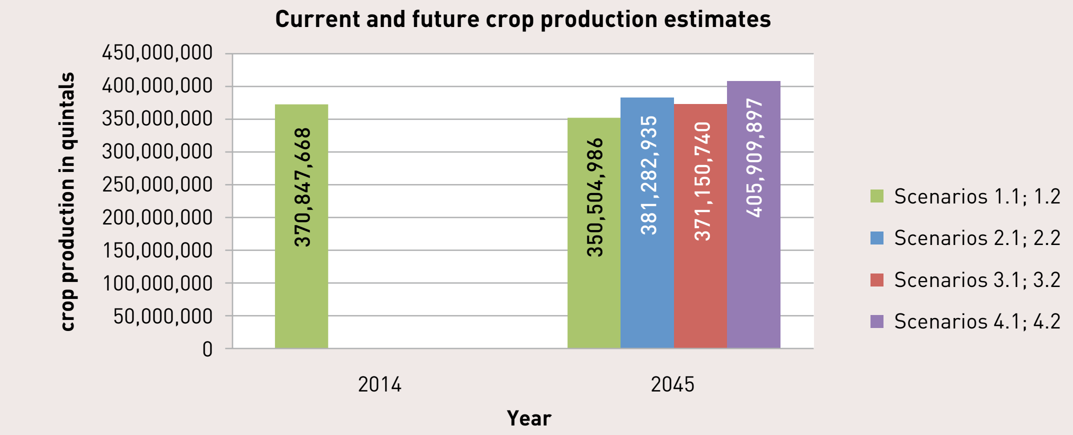
TABLE 13

Deviation of the estimated current crop production from the crop production calculated using CSA productivity per hectare data

Agro-ecological zone	Crop production in quintals (calculated using CSA productivity data)	Crop production estimates in quintals (crop production – soil depth relationship)	Deviation (in percent)
Dry Kolla	33,807,830	34,158,800	1.04
Moist Kolla	29,318,320	30,752,300	4.89
Wet Kolla	10,966,758	12,024,800	9.65
Dry Weyna Dega	42,046,762	40,606,700	−3.42
Moist Weyna Dega	129,801,393	114,933,000	−11.45
Wet Weyna Dega	76,077,747	86,321,100	13.46
Dry Dega	6,921,901	5,656,890	−18.28
Moist Dega	63,376,631	61,644,000	−2.73
Wet Dega	36,607,920	39,792,900	8.70
Moist High Dega	2,556,232	2,284,430	−10.63
Wet High Dega	868,402	805,758	−7.21
Total	**432,349,896**	**428,980,678**	**−0.78**

FIGURE 42

Comparison of current and future crop production in 2045, considering the implementation of different management options (4 scenarios)



other country level data on crop production available, authors had to calibrate the model targeting the crop productivity data provided by CSA.

Considering these issues and the fact that the study modelled the distribution of conservation structures, fertilizer application, and soil depths, using the estimated crop production at pixel level can be misguiding. At pixel level, the actual distribution of the two management options and soil depth could easily differ from the data here. However, for bigger units (e.g., the wereda level) the figures provided by this model can be considered reliable.

When comparing crop production estimates of the current situation with the estimated crop production of the different scenarios in 30 years, the difference can be shown between the two management options and future crop production (*Figure 42*).

Scenarios 1.1 and 1.2 represent 'business as usual', assuming fertilizer application and conservation structure distribution remains as is for the next 30 years. By doing so, crop production after 30 years would be reduced by approximately 20 million quintals. This reduction (in this model) is solely related to soil erosion. Comparing these two scenarios with Scenarios 3.1 and 3.2 shows that with the construction of conservation structures on all croplands with slopes > 8 per cent, this dynamic can be halted and crop production maintained at the current level. The increase in crop production may seem strange at a first glance, as despite the conservation structures, erosion still occurs and thus production should be smaller when compared to Scenarios 1.1 and 1.2 in 2014. However, as conservation structures also change the water availability and reduce the damages which erosive processes have on yields (both are included in the crop production – soil depth relationships defined in this analysis), an increase in crop production can occur.

Scenarios 2.1 and 2.2 show that fertilizer application on all croplands (without further expansion of conservation structures) has a bigger impact on crop production than the expansion of conservation structures without further fertilizer application (Scenarios 3.1 and 3.2). In the long run however, the management options of Scenarios 2.1 and 2.2 are still detrimental, as on-going soil erosion will reduce the depth to a degree where production will decline heavily – with or without fertilizer. Thus, Scenarios 4.1 and 4.2 seem to be the best option for increasing production, as the effect of the fertilizer is fully used while conserving the areas most susceptible to soil erosion. This is also reflected by the total crop production of this scenario – it is substantially bigger than the yields of the other scenarios.

While the comparison of these scenarios at national level clearly shows which measure has the biggest potential for increasing future crop production, it may not be the most beneficial choice in all areas, nor the most beneficial in economic terms. In order to find out which scenario brings the biggest economic benefit, a CBA (one of the main ways that economists use to analyse major development proposals and environmental problems) was performed for each at pixel level.

2.5 Component 5: Financial Cost-Benefit Analysis (CBA)

An understanding of the factors that may influence farmers in making investments in SLM technologies allows policy-makers to design policies more effectively. Without sufficient profitability, other factors that condition adoption become less relevant. A financial cost-benefit analysis is used to evaluate the profitability of SLM investment under various scenarios. The objective of a CBA is to compare the present value of the stream of benefits (positive effects) and the present value of all investments and recurrent costs (negative effects). A CBA can either be carried out from the farmers' perspective (financial CBA) or society as a whole (economic and social CBA). In this case, authors considered the former as benefits to society as a whole (e.g., off-site impacts of soil erosion) were not considered due to limited availability of spatially explicit data.

A CBA has the following components: determination of evaluation criteria; identification of effects (costs and benefits); quantification in physical terms of the effects; valuation of effects; determination of time horizon; weighing of the costs and benefits in time (discounting) and sensitivity analysis (de Graaff, 1996). The most commonly used CBA evaluation criteria are the benefit/cost ratio (B/C ratio), the net present value (NPV) and the internal rate of return (IRR). For this study, NPV and IRR are used as evaluation criteria. If the NPV is positive, it means the investment on SLM measures was profitable. However, if NPV is negative, the costs outweigh the benefits benefits, meaning that the investments in SLM measures were not economical. Similarly, if the IRR is greater than the existing opportunity cost of capital (discount rate), then investment on SLM measures is acceptable, and otherwise not. In the financial CBA, a discount rate of 12.5% (NBE 2014) and a lifetime of 30 years are assumed.

Due to the uncertainty in the value of some parameters (e.g., prices and costs) a sensitivity analysis was carried out to test the robustness of the outcome of the financial cost-benefit analysis.

Although most important parameters used in the analysis are carefully computed and validated, this CBA had the following limitations:

1) Due to a lack of pixel or village specific information, most parameters (e.g. prices of inputs and crops, amount of fertilizer use) considered in the analysis are average parameters obtained either at provincial, regional, or national level;
2) As the distribution of SLM investments/conservation structures was modeled, the costs and benefits associated for each structure type were not computed, instead average costs and benefits were used in the analysis, and;
3) The CBA mainly focused on direct and measurable benefits (crop production change due to SLM investments) but other private benefits (e.g., crop residue due to change in crop production and other associated benefits) and societal benefits are not included in the analysis. These omissions will underestimate the benefits of investments in SLM.

These limitations suggest that caution is needed in interpretation of results.

2.5.1 Data preparation for the CBA at pixel level

The CBA was performed for the eight different scenarios described below to determine the most profitable scenario at pixel level, and considering the limitations faced at pixel level, also for clusters of pixels and administrative units. For each of the parameters included in the different scenarios (*Table 14*), authors attributed the costs and the benefits in Ethiopian Birr (ETB). The following scenarios were considered.

- **Scenario 1.1:** CBA including the distribution of currently existing conservation structures and the currently fertilized croplands. This scenario represents "business as usual" or a baseline scenario, as no additional investments are considered;

- **Scenario 1.2:** Equivalent to Scenario 1.1, but including the costs and benefits of planting fodder grass on the conservation structures;
- **Scenario 2.1:** CBA including the distribution of current conservation structures and assuming the application of fertilizer on all croplands;
- **Scenario 2.2:** Equivalent to Scenario 2.1, but including the costs and benefits of planting fodder grass on the conservation structures;
- **Scenario 3.1:** CBA including the distribution of current conservation structures, assuming the additional construction of conservation structures on all croplands with slopes > 8 per cent, and the currently fertilized croplands;
- **Scenario 3.2:** Equivalent to Scenario 3.1, but including the costs and benefits of planting fodder grass on the conservation structures (existing and new);
- **Scenario 4.1:** CBA including the distribution of current conservation structures, assuming the additional construction of conservation structures on all croplands with slopes > 8 per cent, and assuming the application of fertilizer on all croplands, and;
- **Scenario 4.2:** Equivalent to Scenario 4.1, but including the costs and benefits of planting fodder grass on the conservation structures (existing and new).

Table 14 shows an overview of the scenarios and parameters involved. From Scenario 1.1 to Scenario 4.2, incremental change in the benefits and costs related to the adoption of conservation structures are considered. The following sections then describe how the costs and benefits for each of the parameters were measured.

Crop production benefits

The crop production estimation in this study (described in the previous chapter) already included some of the costs and benefits related to the different management options. For example, estimates already reflect the biophysical benefits from applying fertilizer, of increased water availability and crop production reduction because of cropland area loss due to conservation structures, and decline in soil depth related to erosion (or increase in crop production due to the increase in soil depth related to deposition). With these effects already included in production, implementing the financial CBA at pixel level was less complex as the benefits from production and applied management options could be directly calculated from the amount of crop production. Only fertilizer costs, construction/maintenance costs related to the conservation structures, and nutrient depletion of soils due to the enrichment ratio were considered as additional costs in the financial CBA.

Two crop prices sources were used to attribute a monetary value to the crop production:

- Average retail prices of crops for 84 market locations distributed across various regions considered, obtained from the CSA 'Annual average retail prices of goods and services July 2012 – June 2013' (CSA 2013c), and;
- Average farm gate prices for the different zones in January 2013 (CSA 2014).

The first dataset provides point locations with average retail prices, which allows attributing crop prices to the agro-ecological zones for which the crop supply baskets were defined. However, average retail prices do not represent farm gate prices, as they include additional costs and benefits until the product reaches the final consumers. The second dataset provides farm gate prices, but at the zonal level, which makes the attributing to the agro-ecological zones/crop supply baskets more difficult. The prices for crop supply baskets were therefore assessed the following way:

1. Assessing the mean difference between the average retail prices and the farm gate prices by comparing the point data average retail prices within a specific administrative zone with the farm gate prices of that zone. This allowed for the adjustment of the point data average retail prices by the mean difference assessed to obtain farm gate prices;
2. Calculating average farm gate prices from adjusted average retail price point data for each agro-ecological zone, and;
3. Defining the price for one kg of crop yield for each crop supply basket based on the summarized price information per agro-ecological zone and the percentage of crop occurrence defined by the crop supply basket.

Once the price for each crop supply basket defined[1], the yield benefits for each scenario and year could be computed at pixel level.

---

[1] Crop basket prices are derived from 2012/2013 average retail and farm gate prices

TABLE 14

Parameters included in the CBA for each scenario

Scenarios Parameters	1.1	1.2	2.1	2.2	3.1	3.2	4.1	4.2
Crop production benefits related to the scenario (different management options result in different crop production)	×	×	×	×	×	×	×	×
Fodder grass benefits related to the scenario (extent of conservation structures)		×		×		×		×
Fodder grass plantation costs related to the scenario (extent of conservation structures)		×		×		×		×
Fertilizer costs related to current fertilizer application	×	×			×	×		
Fertilizer costs related to fertilizer application on all croplands			×	×			×	×
Maintenance cost of current conservation structures (labour input)	×	×	×	×	×	×	×	×
Construction costs of additional conservation structures (labour input)					×	×	×	×
Cost of tools related to the construction of additional conservation structures					×	×	×	×
Maintenance cost of additional conservation structures (labour input)					×	×	×	×
Cost/benefit of eroded/deposited nutrients (only N and P were considered) for erosion/deposition rates estimates assuming the current distribution of conservation structures	×	×	×	×				
Cost/benefit of eroded/deposited nutrients (only N and P were considered) for erosion/deposition rates estimates assuming the current distribution of conservation structures and additional structures on all croplands with slopes › 8%					×	×	×	×

Fertilizer costs

The 'Report on Farm Management Practices' from the CSA agricultural sample survey of 2012/2013 (2013b), was used to define the croplands treated with fertilizer for each administrative zone, and also provides information on the amounts of fertilizer (UREA and DAP, although no information on the shares of each) applied. This allowed authors to calculate the amounts of fertilizer used on each pixel where it is applied. Without information on the respective shares of UREA and DAP, the study calculated the price for one kg of fertilizer from the national average prices (Shahidur et al. 2012). This resulted in a fertilizer price of 14.64 ETB per kg[2], which is a rather rough estimate as the same share of UREA and DAP is not necessarily used.

For Scenarios 1.1, 1.2, 3.1, and 3.2, authors could calculate fertilizer cost for each pixel by multiplying the amount applied (in kg) by 14.64 ETB.

For Scenarios 2.1, 2.2, 4.1, and 4.2 (application of fertilizer on all croplands) it was assumed that same amount of fertilizer is applied on 'new' pixels as on the cropland pixels currently treated with fertilizer, within each administrative zone. Considering that current fertilizer use is below the optimum, these scenarios may not show the optimal situation/yields that could be obtained when applying fertilizer as recommended by research. Thus crop production estimates were calibrated considering current fertilizer application. Without knowing how optimal fertilizer use affects yields, the study assumed that fertilizer amounts applied on all cropland pixels are the same as on the cropland pixels currently treated with fertilizer, otherwise, it would not be possible to properly estimate the yields. The fertilizer cost of these scenarios was calculated the same way as above, by multiplying the amount of fertilizer applied by 14.64 ETB.

Conservation structure costs

Several costs are related to the building of conservation structures: construction costs, maintenance costs, and the cost of tools. Although different types of structures (soil bund, fanya juu bund, and terraces) have different costs, average construction and maintenance costs were considered because the distribution of conservation structures was modelled, authors were not able to distinguish costs by type of structure.

From the conservation structure distribution model, the length of conservation structures in meters per pixel could be extracted and used to calculate the cost per pixel. As the construction and maintenance is often done during off-season, their costs relate to off-season rural wages (Lakew et al. 2005), which vary across the study area. However, authors did not find sufficient information to model these variations and SLM experts were thus consulted to obtain an estimate. Based on this a national daily wage rate of 40 ETB in 2013 was assumed to compute the following costs[3]:

- Construction costs: 5 m of structures/day at 40 ETB/day (8 ETB/m of structure)
- Maintenance cost: 50 m of structures/day at 40 ETB/day (0.8 ETB/m of structure)
- Cost of tools: 200 ETB/1000 m of structures (0.2 ETB/m of structure)

While the construction costs (tools and labour) are one-time, maintenance of the structures has to be performed on an annual basis over 15 years until they are stabilized. As the different scenarios only considered existing structures (Scenarios 1.1, 1.2, 2.1, and 2.2) or both existing and new (Scenarios 3.1, 3.2, 4.1, and 4.2), different costs related to the conservation structures had to be considered for different scenarios.

For Scenarios 1.1, 1.2, 2.1, and 2.2 (only considering existing structures) only maintenance costs (labour based on the metres of structures per year) over 5 years were included in the CBA. As the structures already existed, no construction costs were applied. Additionally authors did not know the age of the specific structures, so they were assumed to be 10 years of age and only needing maintenance for another 5 years.

For Scenarios 3.1, 3.2, 4.1, and 4.2 (existing and new structures), a maintenance cost over 5 years was assumed for the existing structures. For the new structures the one-time construction costs (labour and tools based on the meters of structures per pixel) were assumed to be in the first year, and the maintenance costs (labour per meter of structure per pixel) started in the second year, lasting for 15 years.

[2] UREA and DAP prices from 2012 according to Shahidur et al. 2012. Due to the high variability of the prices over the years according to Shahidur et al. 2012, adjustments for inflation for the price in 2013 were not performed; prices are representative only.

[3] Due to spatial variability and lack of data costs are expert-based estimates and rather representative than spatially accurate.

Cost/benefit of nutrient losses/gains due to soil erosion

As discussed in the crop production benefits chapter, the estimation of crop production already included costs related to the reduction of soil depth from erosion (and gains related to the increase of soil depth due to deposition). Due to the enrichment ratio of soil erosion, there are more nutrients washed away than contained in eroded soil. This means that parts of the lost nutrients were not considered in the estimation of the crop production, and were therefore included as an additional element in the CBA.

Only N (nitrogen) and P (phosphorous) were considered, as information on other nutrients was not available. The amounts of N and P for each soil type (derived from the literature) are shown in *Table 15*.

To derive the costs or gains related to these nutrients, authors calculated the amounts of fertilizer needed to replace them (Shahidur et al. 2012). As a part of the nutrient loss is already included in the crop production estimation, half of the nutrient replacement cost was included in the CBA[4]:

- 1kg of P is equivalent to 2kg of DAP, which costs 32 ETB
- 1kg of N is (almost) equivalent to 2kg of UREA, which costs 26 ETB

As Scenarios 1.1, 1.2, 2.1, 2.2, and Scenarios 3.1, 3.2, 4.1, and 4.2 show different erosion/deposition schemes due to different extents of conservation structures, N and P costs and benefits were calculated in two versions. By combining soil type data with the erosion/deposition rates, the costs and benefits of N and P erosion and deposition were computed for the two schemes (Scenarios 1.1 to 2.2, and 3.1 to 4.2).

Fodder grass production costs and benefits

The return from investments on conservation structures is not immediate, but structures involve immediate costs due to construction, maintenance, and taking productive land out of production. Given that most farmers are poor, they may opt not to adopt if they do not see immediate benefits from adoption. Growing high value crops (e.g., cash crops, grain and fodder legumes) on the structures and combining structures with complementary inputs (e.g., fertilizer, improved seeds) can help farmers to generate immediate benefits from structures. In this study, authors considered inorganic fertilizer and growing fodder grass on the structures given that livestock feed is critical in the Ethiopian Highlands. The fodder grass production is considered in Scenarios 1.2, 2.2, 3.2, and 4.2. Using the length of conservation structures, the costs and benefits of fodder grass cultivation is derived. It was assumed that 1 m^2 of fodder grass could be cultivated per meter of structure.

The plantation of fodder grass on the structures is a one-time task, and authors assumed that 65 metres of structures could be planted per day at a cost of 40 ETB/day (approximately 0.62 ETB/m of terraces) (Lakew et al. 2005). The benefits of fodder grass vary depending on the agro-ecological zone. The type of grass cultivated and benefits per metre of structure are shown in *Table 16*:

TABLE 15

Soil types considered in the study area and amounts of N and P (in kg) per tonne of soil

Dominant soil type	N (kg) per tonne of soil	P (kg) per tonne of soil
Alisols *	3.20	0.009
Andosols	3.63	0.007
Arenosols	0.40	0.008
Chernozems *	3.20	0.009
Calcisols	1.97	0.007
Cambisols	2.27	0.009
Fluvisols	3.20	0.012
Gypsisols *	3.20	0.009
Leptosols	1.90	0.008
Luvisols	1.97	0.014
Lixisols *	3.20	0.009
Nitisols	2.30	0.007
Phaeozems	4.20	0.010
Regosols	2.10	0.019
Solonchacks	0.95	0.009
Solonetz *	3.20	0.009
Vertisols	2.4	0.008

* no information on N and P was available and the national average was thus considered

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[4] Prices of fertilizer are based on Shahidur et al. 2012

TABLE 16

Benefits of fodder grass per meter of conservation structure by grass type and agro-ecological zone

Agro-ecological zone	Grass	Elephant grass	Benefit per meter of structure (in ETB)[5]
Dry Kolla	×		2.00
Moist Kolla		×	4.00
Wet Kolla		×	5.00
Dry Weyna Dega	×		2.50
Moist Weyna Dega		×	5.00
Wet Weyna Dega		×	6.00
Dry Dega	×		2.00
Moist Dega	×		3.00
Wet Dega		×	4.00
Moist High Dega	×		2.50
Wet High Dega	×		3.00

Based on this, benefits of fodder grass for existing structures were calculated (Scenarios 1.2 and 2.2), as well as for the distribution of conservation structures on all croplands with slopes > 8 per cent (Scenarios 3.2 and 4.2).

2.5.2 CBA for the different scenarios

Having all costs and benefits defined at pixel level, the CBA for the eight different scenarios could be performed. For each scenario, net benefits were calculated per year, from 2014 (Year 0) to 2045 (Year 30). *Table 17* shows the discount rate, costs, and benefits considered in each scenario.

Due to the heavy data load and the related computation time when performing such an analysis at pixel level it was not possible to perform a sensitivity analysis at pixel level to determine how changes in prices and costs affect the outcome of the CBA. Sensitivity analysis and the IRR were therefore performed at aggregate wereda level. While this brings some generalization compared to the pixel level, it still shows how changes in the costs and prices affect the profitability of the different management options. The results of the sensitivity analysis are presented in *Chapter 3.3*.

To assess at which locations/pixels which scenario is likely to bring the highest benefit, the NPV was computed over the chosen time horizon of 30 years for each scenario. *Table 18* shows the value of the NPV, derived from the pixel based analysis.

This analysis shows that all scenarios show a positive NPV on average, with the majority of the pixels having a positive NPV. The NPV gradually increases (from Scenario 1.1, 2.1, and 3.1, to 4.1 or 1.2, 2.2, 3.2, and 4.2), indicating that the full swing of measures (conservation on all croplands steeper than 8 per cent, fertilizer application everywhere, and fodder grass on all structures; i.e., Scenario 4.2) brings the highest NPV on average and that scenarios including the plantation of fodder grass on the structures are generally more profitable than the corresponding scenario without grass.

Authors further analysed the result of the calculation of the NPV at pixel level as well as for different administrative units. The findings of these analyses are presented in the next chapter.

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[5] Due to spatial variability and lack of data, fodder grass prices are expert-based estimates and representative rather than spatially accurate.

TABLE 17

Discount rate and costs and benefits associated with the different scenarios

(The CBA was calculated for each year [2014 (Year 0) to 2045 (Year 30)]. Some of the costs were only considered in the year[s] specified in the table)

Scenario	Discount rate	Costs	Benefits
1.1	12.5%	Fertilizer costs (current application) Maintenance of existing structures (year 0 – year 4) N & P loss due to erosion (current structure distribution)	Crop production N & P gain (deposition)
1.2	12.5%	Fertilizer costs (current application) Maintenance of existing structures (year 0 – year 4) N & P loss due to erosion (current structure distribution) Fodder grass plantation on current structures (year 0)	Crop production Fodder grass benefits N & P gain
2.1	12.5%	Fertilizer costs (application on all croplands) Maintenance of existing structures (year 0 – year 4) N & P loss due to erosion (current structure distribution)	Crop production N & P gain
2.2	12.5%	Fertilizer costs (application on all croplands) Maintenance of existing structures (year 0 – year 4) N & P loss due to erosion (current structure distribution) Fodder grass plantation on current structures (year 0)	Crop production Fodder grass benefits N & P gain
3.1	12.5%	Fertilizer costs (current application) Maintenance of existing structures (year 0 – year 4) N & P loss due to erosion (structures on all croplands with slopes › 8% & existing structures) Construction of new structures (tools, labour – year 0) Maintenance of new structures (year 1 – year 15)	Crop production N & P gain
3.2	12.5%	Fertilizer costs (current application) Maintenance of existing structures (year 0 – year 4) N & P loss due to erosion (structures on all croplands with slopes › 8% & existing structures) Construction of new structures (tools, labour; year 0) Maintenance of new structures (year 1 – year 15) Fodder grass plantation on new & existing structures (year 0)	Crop production Fodder grass benefits N & P gain
4.1	12.5%	Fertilizer costs (application on all croplands) Maintenance of existing structures (year 0 – year 4) N & P loss due to erosion (structures on all croplands with slopes › 8% & existing structures) Construction of new structures (tools, labour; year 0) Maintenance of new structures (year 1 – year 15)	Crop production N & P gain
4.2	12.5%	Fertilizer costs (application on all croplands) Maintenance of existing structures (year 0 – year 4) N & P loss due to erosion (structures on all croplands with slopes › 8% & existing structures) Construction of new structures (tools, labour; year 0) Maintenance of new structures (year 1 – year 15) Fodder grass plantation on new & existing structures(year 0)	Crop production Fodder grass benefits N & P gain

TABLE 18

NPV statistics of the whole study area for each scenario (derived from the pixel based analysis)

NPV statistics for each scenario (ETB/ha)

	1.1	1.2	2.1	2.2	3.1	3.2	4.1	4.2
minimum	-350'967	-350'967	-363'633	-363'633	-377'444	-342'078	-387'233	-350'744
maximum	569'133	569'133	557'311	565'989	542'567	600'400	553'733	607'400
mean	112'744	116'522	113'589	117'356	115'300	126'678	117'311	128'689
standard deviation	51'078	49'100	54'478	52'478	48'400	45'922	52'178	50'156

NPV statistics for each scenario (USD/ha)

	1.1	1.2	2.1	2.2	3.1	3.2	4.1	4.2
minimum	-17'913	-17'913	-18'560	-18'560	-19'265	-17'460	-19'764	-17'902
maximum	29'049	29'049	28'445	28'888	27'693	30'644	28'263	31'002
mean	5'754	5'947	5'798	5'990	5'885	6'466	5'988	6'568
standard deviation	2'607	2'506	2'781	2'678	2'470	2'344	2'663	2'560

CHAPTER

03 Synthesis and discussion of livelihood options

3.1 Achievements and limitations

The ELD Ethiopia Case Study concentrated mainly on the productive functions of Ethiopia's highland ecosystems. The objective was to find out how best to minimize soil degradation and achieve better cropland productivity and longterm sustainability (i.e., reducing on-site impacts). The study further attempted to outline solutions that help to reduce sediment yields in river basins to ensure sustainability of reservoirs for hydropower generation and other purposes such as water supply and small-scale irrigation (i.e., reducing off-site impacts).

The analyses within each of the five components of the case study have resulted in the following spatially explicit datasets at a resolution of 30 m x 30 m:

- Current state and rates of soil degradation – including SLM technologies implemented – as well as resulting crop production and their monetary value (enables discussion of the profitability of currently implemented SLM technologies)
- Profitability of improving current SWC technologies and of introducing improved SLM technologies in areas where SWC structures have not yet been built

This methodology is rather unique: The authors worked with farmers' field size area unit (30m pixels) to perform a spatially explicit economic valuation of SLM technologies. Yet the case study covered a very large area of 600,000 km^2 with over 200,000 km^2 of croplands. The shortcomings of the data used were mentioned in the descriptions of the case study components in *Chapter 2*:

- Lack of spatially explicit data on the distribution of existing conservation structures;
- Lack of spatially explicit data on the distribution of current fertilizer application;
- Lack of data on the current sediment yield in any one of the large river basins in Ethiopia;
- Lack of spatial data for some of the parameters such as the benefits of crop residue use.

Authors had to neglect some parameters or use proxies to produce these layers. This can affect the accuracy of results at the pixel level, whereas results at aggregated levels are more reliable. As soon as more accurate layers become available, this analysis can be run again and thereby improved.

In the scenario analysis, authors did not change the current extent of croplands over the 30 years of scenario development, nor were agronomic changes included, such as plant breeding, plant protection, changes in the farming system, expansion of croplands or other land use types, deforestation, or climate change. The study quantified the on-site impacts of soil erosion by water related to crop production; all other on-site impacts and off-site impacts are not addressed. However, if these were included as variables, the model developed could fairly easily be used to develop scenarios of sustainable agricultural development while maintaining the ecological functions of soil and water. Finally, one might ask whether 30 years is forward-looking enough. Soil erosion is a relatively slow process: over a period of 30 years it will reduce soil depth on cropland by an average of 'only' 6 cm. However, knowing that soil degradation is almost irreversible, authors estimate that it may take as much as 100–300 years for the soil to regain those 6 cm (Hurni 1983), and conclude that soil erosion must be reduced to a minimum.

3.2 Pertinent questions at the national level

How important is soil erosion?

The scenario analysis carried out for the ELD Ethiopia Case Study shows that soil erosion is indeed the most important process of land degradation in the rainfed agricultural areas of Ethiopia. *Table 19* presents the net erosion/deposition totals for the most important land cover classes in the study area, as well as on an average per hectare basis. Soil loss is greatest on croplands, which shows how important

TABLE 19

Comparison of erosion estimates by Hurni (1989) for the whole area of Ethiopia and Eritrea with the erosion estimates of the ELD Case Study

	Soil loss estimates by Hurni (1989) for Ethiopia and Eritrea (total area: 122,190,000 ha)			Soil loss estimates for the ELD Case Study area (total area: 52,205,748 ha)		
Land cover	**Area (%)**	**Soil loss estimate (t/ha/year)**	**Soil loss estimate (t/year)**	**Area (%)**	**Net soil loss estimate (t/ha/year)**	**Net soil loss estimate (t/year)**
Cropland	13.1	42	672,000,000	36.7	20	382,751,711
Perennial crops	1.7	8	17,000,000	2.3	19	21,913,824
Grazing and browsing land	51.0	5	312,000,000	9.3	12	56,176,073
Currently unproductive	3.8	70	325,000,000	4.6	33	78,794,014
Currently uncultivable	18.7	5	114,000,000	0.8	16	6,494,015
Forests	3.60	1	4,000,000	10.02	6	32,419,956
Wood- and bushland	0.08	5	49,000,000	36.21	19	362,535,000
Total	100.00	12	1,493,000,000	100.00	18	941,084,593

it is for farmers and society to minimize soil erosion processes on this type of land use in particular, although the management of all other types needs to be improved as well.

In 1989, Hurni made a first estimate of soil loss for the whole country, including lowland areas, and came up with the figure of 1,493 million tonnes of annual soil loss (Hurni 1989). This estimate is compared with the erosion estimates of the present case study in *Table 19*.

To understand *Table 19* it is important to take note of the following considerations:

- The area considered in the national estimate by Hurni (1989) differs from the area of the present case study, because the latter excludes the lowlands. In Hurni's estimate, 300,000,000–500,000,000 tonnes of soil loss originate from the lowland areas alone, including much of the grazing and browsing areas (51 per cent of the country) and the currently unproductive land (3.8 per cent);
- Second, the two estimates use different definitions of land cover classes, which results in different area shares and erosion estimates (e.g., Grazing and browsing land; Wood- and bushland);
- Third, calibration for the estimates provided by the present case study focused on croplands, in line with the study's main objective, and also due to the rather scarce availability of calibration data for the "Agroforestry", "Wood- and bushland", and "Forests" classes, and;
- Fourth, this case study considered soil erosion and deposition whereas the estimate of Hurni (1989) only accounts for soil erosion.

In conclusion, there are two main explanations for the differences between Hurni's estimates (Hurni 1989; *Table 19*) and the present assessment. First, his study area was larger (first point), and second, considerable investments have been made in SWC over the past 30 years and have had a positive effect on the reduction of soil erosion. In other words, the substantial differences between the two erosion estimates can be attributed to the two different assessment dates, the area coverage, and (land cover) data. It is however questionable whether these factors can fully explain the large differences in the soil loss estimates in tonnes/ha/yr. Further research in the form of data collection (e.g., sediment yields for large catchments) as well as model adaptation and calibration is thus needed.

Why have other change processes not been included in this assessment?

In 30 years, many changes can happen, including population, urbanisation, foreign direct investment, agricultural development (e.g., plant and animal breeding, farm modernisation, farm implements), changes in land use and cover (e.g., cropland expansion, more intensive land use, more irrigation), and last but not least, climate change, which for the Ethiopian Highlands shows certain signals of warming but no precipitation trends yet. All these changes have not been included in the present assessment. Here, the extent of croplands and other land cover classes is assumed to remain the same; it was assumed that crop supply baskets and cropping patterns do not change, the agroclimatic situation remains as today, and climate will be as variable as in the past. Authors are aware that this will not be the reality, however, they do not have sufficient empirical evidence and knowledge about trends for including such parameters in the modelling exercise. In future re-assessments, nevertheless, it would be fairly easy to include new processes and parameters in the model, provided that scientific results will be available.

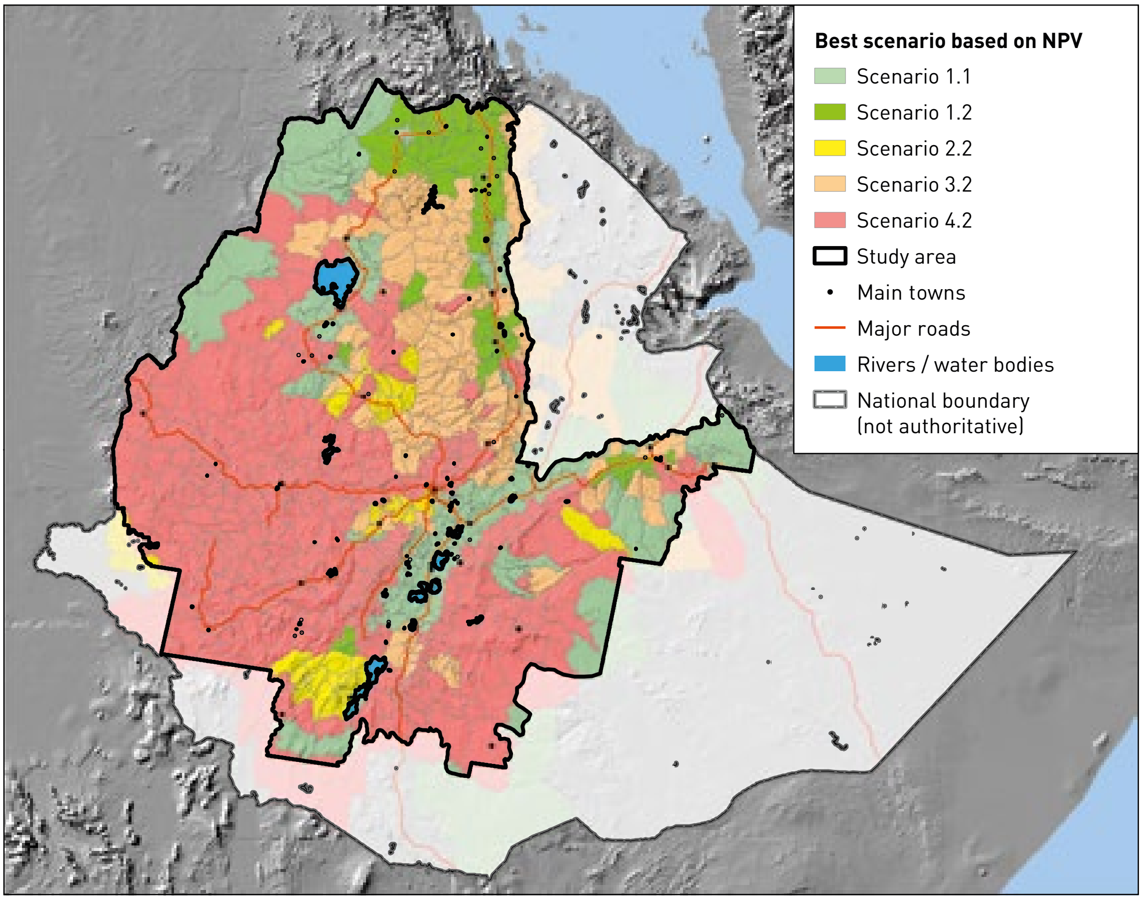
What is the best way to combat soil erosion?

From a national perspective, food security mainly depends on crop production. Preserving the productive functions of cropland ecosystems, therefore, deserves top priority. Authors developed eight scenarios of current and future use of the current

FIGURE 43

The best scenario based on NPV for each wereda in the case study area

(Within each wereda, the scenario represented by the greatest number of pixels was assumed to be the best scenario for the entire wereda)



existing croplands, ranging from business as usual (Scenario 1.1) to conservation of all croplands on slopes > 8 per cent, coupled with moderate fertilizer use on all croplands and the planting of fodder grasses on all conservation structures (Scenario 4.2), with 6 more scenarios in-between (see *Table 1*). The economics of the 208 million cropland pixels (900 m^2 each) in the rainfed croplands was assessed, to determine the scenario with the best NPV for each pixel. The pixel level information was then summarized for each wereda, with results presented on a map (*Figure 43*).

The map shows that in fairly flat areas, where there are no conservation structures, Scenario 1.1 (business as usual) is the best option. This means that the management options considered in this case study either already exist (i.e., fertilizer application) in these areas, or that their benefit is too small for them to be viable. In areas where soil and water conservation has been extensively implemented, such as in Tigray Region and parts of Wello, the highest NPV is achieved with Scenario 1.2 (adding grass on existing bunds, but no additional fertilizer). Much of the southern half of Ethiopia's rainfed croplands performs best with the full swing of measures: conservation on all lands steeper than 8 per cent, fertilizer application everywhere, and fodder grass on all structures (Scenario 4.2). In Amhara Region and in parts of the Harari area in Oromia Region, the combination of conservation structures with fodder grass achieves the best NPV (Scenario 3.2). Scenario 2.2 (adding grass on existing bunds, applying fertilizer on all croplands) is the best option for only those few weredas that already have a fair amount of conservation structures.

Across the entire case study area, Scenario 1.1 (business as usual) has an NPV of 110,920 ETB/ha of cropland, while the NPV of the best scenario (see *Figure 43*) averages 132,350 ETB/ha of cropland. This means that implementing the best management option or a combination of management options (fertilizer, structures, grass on structures) as identified in this analysis could increase the NPV of croplands by almost 20 per cent.

What intervention options are there?

In a further analysis at the national level, the NPV of the best scenario was compared with current net soil erosion rates in an attempt to understand where and how SLM investments affect soil erosion and the impacts on individuals and society. Such information can assist policy-makers and development partners to prioritize resources allocation and development interventions. The analysis revealed that in most areas the farmers themselves can implement the interventions, although the governments will need to initiate and organize the activities on the ground. Based on the analysis, four classes of intervention types were developed for all croplands (*Table 20*).

The first two classes (green and orange) are areas where the NPV of the best scenario is more than the case study average of 12,000 ETB per pixel or 132,000 ETB/ha (5,077 EUR/ha). In one class (green) this high NPV is combined with erosion rates below the case study average of 2 tonnes per pixel or 22 tonne/ha; in the other class (orange) the high NPV coincides with above-average erosion rates. The other two classes were defined the same way, but for below-average best scenario NPVs, combined either with low (yellow) or high (red) erosion rates. *Figure 44* shows how these classes are distributed

TABLE 20

Comparison of the most profitable scenario (highest NPV of all scenarios) with current soil erosion/deposition rates

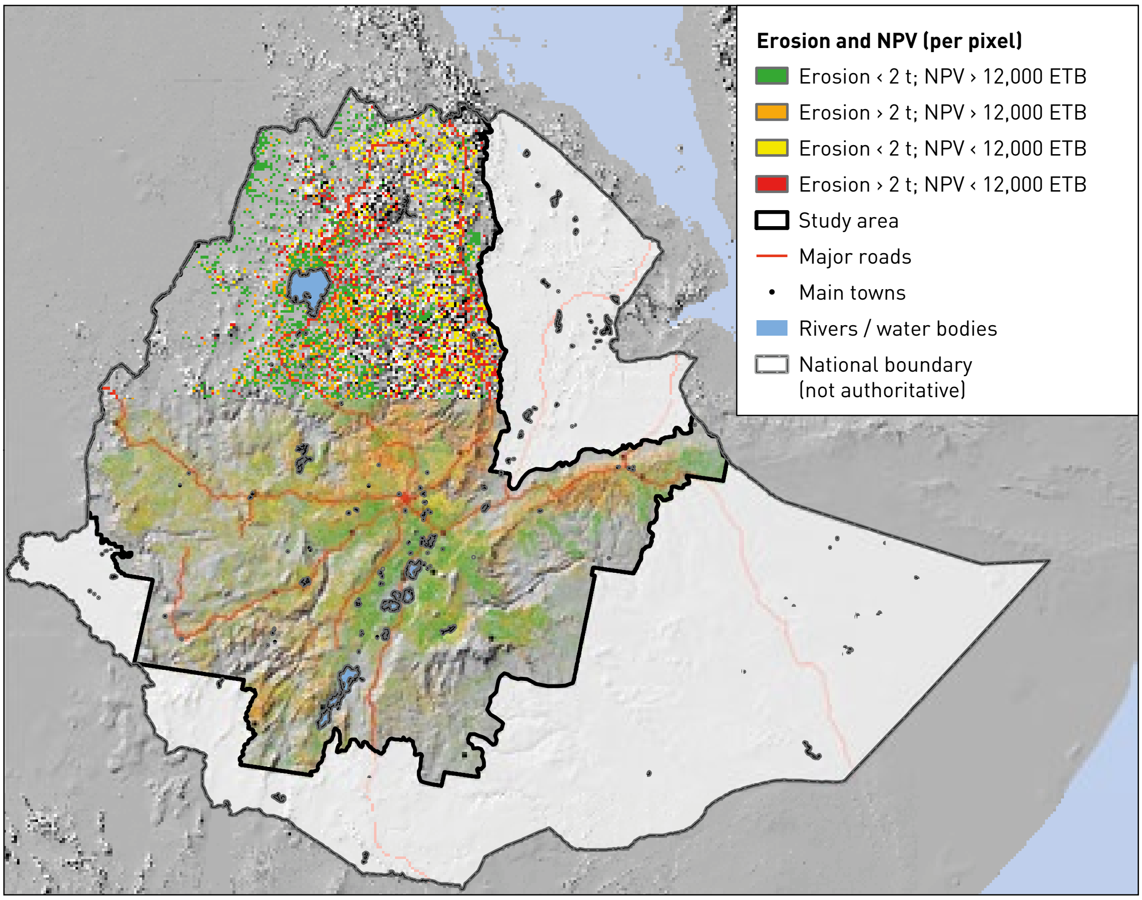
(Currency exchange from August 2014, where 1 EUR = 26 ETB. One pixel is 900 m^2)

	Share of cropland area (%)	
NPV › 5077 EUR per ha	48.4	19.2
NPV ‹ 5077 EUR per ha	16.1	16.3
	Soil erosion ‹ 22 t/ha	Soil erosion › 22 t/ha

FIGURE 44

Combination of the best scenario's NPV with current soil erosion rates at pixel level to support policy formulation

(Currency exchange from August 2014, where 1 EUR = 26 ETB. One pixel is 900 m^2)



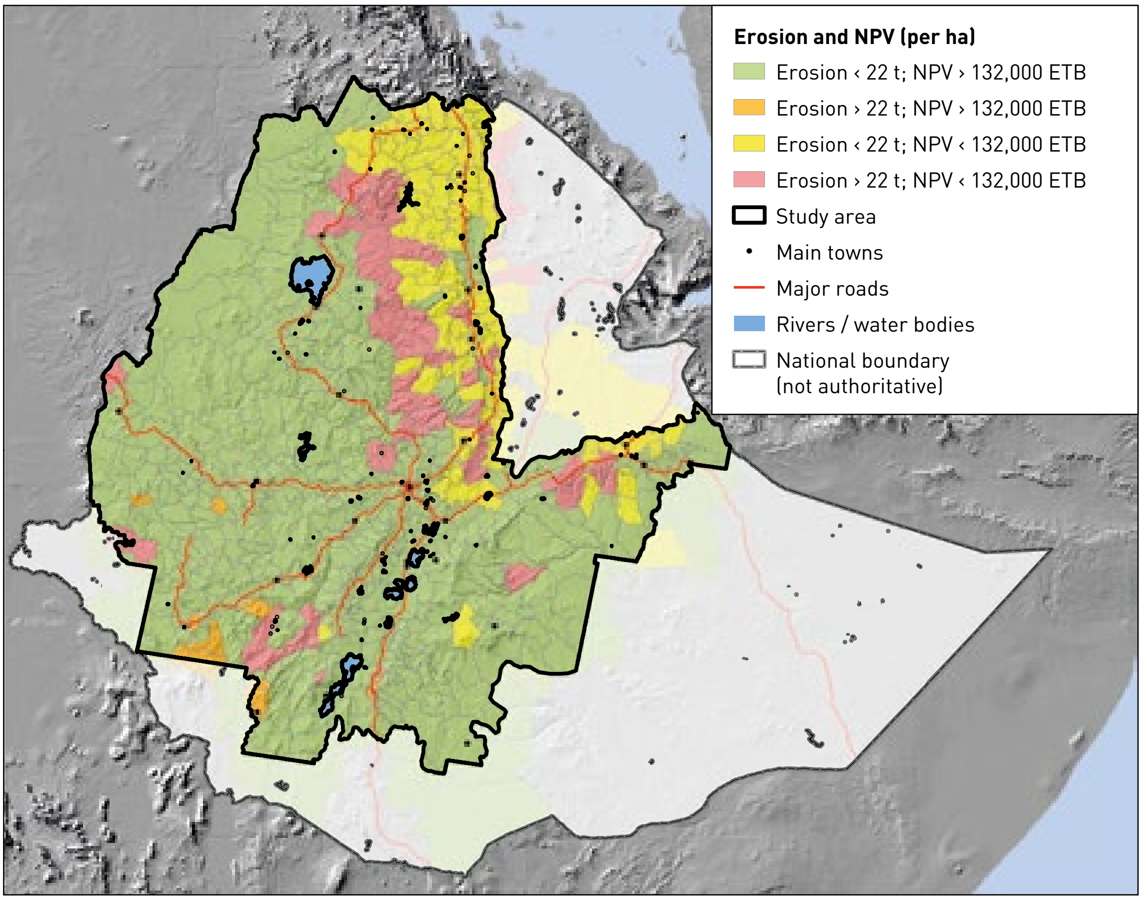
across the case study area at the pixel level. *Figure 45* summarizes this information at the wereda level in order to achieve a better visualization and reduce the data inaccuracies occurring at the pixel level.

Figures 44 and *45* show whether the best scenario's NPV in a given area is above or below the case study average and whether the current erosion rate is above or below the case study average. By combining the two aspects, these maps reveal in which areas or weredas farmers have a comparatively high incentive for implementing the best scenario: This is the case where the best scenario's NPV is above the case study average (**green** and **orange**). In the other areas, below-average NPVs offer little incentive (**yellow** and **red**). In addition, the maps also show where current erosion rates are below the case study average (**green** and **yellow**) and where they are above (**orange** and **red**). Due to effects such as the siltation of dams, erosion also generates costs to society as a whole. From this point of view the maps show whether the incentives for individuals are in agreement or in disagreement with those for society as a whole.

As shown in *Figure 45*, the green areas (high NPV, low erosion) extend across most lowland areas and flatter areas, as well as large parts of the southern and north-western highlands. The yellow areas (low NPV, low erosion) appear where conservation structures have already been built on nearly all croplands, such as in Tigray Region and in parts of Wello and Harari. The red areas (high NPV, high erosion) are found in North Gonder, Wello, North Shewa, Harari, and Omo, where the landscape is

FIGURE 45

Combination of the best scenario's NPV with current soil erosion rates at wereda level to support policy formulation
(Currency exchange from August 2014, where 1 EUR = 26 ETB)



rugged and yields are low. With regard to policy implications, this analysis shows that farmers will need little support in green areas, but full investment support in red areas. Yellow and orange areas may require some support, particularly where erosion is high (orange) and reservoirs exist downstream, such as in the Tekeze, Abbay, Omo-Gibe and Wabe Shebelle basins.

It is important to note that the scenario with the highest NPV has the highest individual benefit, but not necessarily the highest benefit for society as a whole in terms of reducing soil erosion: if the highest NPV can be achieved without building conservation structures, erosion rates will not be reduced. However, policy implications can be further differentiated by comparing *Figure 45* (erosion and NPV per wereda) with *Figure 43* (best scenario based on NPV) and *Figure 15* (model of the current distribution of conservation structures) and considering the different management options and their benefits both for individuals and for society as a whole.

The models used in the ELD Ethiopia Case Study are based on a financial CBA, considering only the benefits and costs for individuals. Further studies are needed to include the full benefits and costs of the society and to perform a social and economic CBA. However, the models presented in this study are capable of providing detailed costing proposals for all considered categories and any area unit, be it a selected watershed, region, zone, wereda, or even Kebele.

What can be learned from the CBA?

The most encouraging result of this case study is that all eight scenarios developed provide a positive net present values (NPV) for improved SLM technologies over the coming 30 years, from the case study level down to the wereda level. This means that for the average farmer in the case study area it pays to invest now in structures which are capable of reducing soil erosion and retaining run-off where necessary, and which will eventually develop into outward sloping terraces within 5–15 years after the initial investment. The NPV will increase considerably if farmers additionally plant grass on the structures; in most cases the benefits of grass are higher than the benefits of applying moderate amounts of fertilizer (80–120 kg/ha/yr).

The CBA considered SLM technologies on all croplands, starting with SWC structures on all crop-

TABLE 21

Net present values (NPVs) of all scenarios by region

(Currency exchange from August 2014, where 1 USD = 20 ETB)

	NPV by region and scenario (ETB/ha)							
Region Name	**1.1**	**1.2**	**2.1**	**2.2**	**3.1**	**3.2**	**4.1**	**4.2**
Tigray	100,715	106,933	95,152	101,370	103,284	104,716	99,096	100,528
Afar	67,516	68,002	57,972	58,458	65,709	74,061	58,262	66,614
Amhara	93,731	99,659	91,564	97,492	95,455	106,317	94,485	105,347
Oromia	122,343	124,301	125,533	127,491	125,138	137,844	129,318	142,024
Somali	142,133	142,468	132,233	132,569	143,742	146,708	137,689	140,656
Benishangul-Gumuz	125,536	126,133	131,239	131,836	128,309	141,518	135,199	148,409
S.N.N.P	120,690	126,161	123,715	129,186	124,268	137,970	128,594	142,296
Gambella	115,731	116,341	119,377	119,987	117,943	133,482	122,485	138,023
Harari	138,857	143,107	126,880	131,131	143,596	148,581	138,004	142,990
Addis Abeba	137,190	137,193	131,066	131,069	140,747	150,498	137,774	147,525
Dire Dawa	58,292	63,379	48,573	53,660	58,815	63,771	51,036	55,992
TOTAL	**112,754**	**116,522**	**113,593**	**117,361**	**115,302**	**126,679**	**117,317**	**128,694**

	NPV by region and scenario (in USD/ha)							
Region Name	**1.1**	**1.2**	**2.1**	**2.2**	**3.1**	**3.2**	**4.1**	**4.2**
Tigray	5,140	5,458	4,857	5,174	5,272	5,345	5,058	5,131
Afar	3,446	3,471	2,959	2,984	3,354	3,780	2,974	3,400
Amhara	4,784	5,087	4,673	4,976	4,872	5,426	4,823	5,377
Oromia	6,244	6,344	6,407	6,507	6,387	7,036	6,600	7,249
Somali	7,254	7,272	6,749	6,766	7,337	7,488	7,028	7,179
Benishangul-Gumuz	6,407	6,438	6,698	6,729	6,549	7,223	6,901	7,575
S.N.N.P	6,160	6,439	6,314	6,594	6,343	7,042	6,563	7,263
Gambella	5,907	5,938	6,093	6,124	6,020	6,813	6,252	7,045
Harari	7,087	7,304	6,476	6,693	7,329	7,584	7,044	7,298
Addis Abeba	7,002	7,002	6,690	6,690	7,184	7,681	7,032	7,530
Dire Dawa	2,975	3,235	2,479	2,739	3,002	3,255	2,605	2,858
TOTAL	**5,755**	**5,947**	**5,798**	**5,990**	**5,885**	**6,466**	**5,988**	**6,569**

lands steeper than 8 per cent and adding moderate application of fertilizer and, importantly, grass planting on all structures. If all three measures are implemented – which does not necessarily achieve the highest NPVs – crop production will increase by nearly 10 per cent in 30 years; the management option with the highest NPV – which does not necessarily include all measures – still achieves an average increase by 7 per cent in 30 years. *Table 21* shows NPVs of all scenarios by region, in ETB/ha.

In the view of the authors, the eight scenarios presented above are a modest, but realistic vision. This vision does not include the benefits of potential agricultural developments such as new crop varieties, maximum fertilizer application, and best agricultural management. Due to the omission of such additional management practices it is likely that the benefits have been underestimated. These scenarios focus above all on achieving sustainable ecosystem functions with regard to soil and water in the long-term. The least promising scenario is business as usual. Although SWC has already been implemented on an assumed 18 per cent of croplands over the past four decades, this study concludes that all sloping croplands need to be treated. This concerns 77 per cent of Ethiopia's croplands, as only 23 per cent of croplands are on slopes smaller than 8 per cent.

What are the total investment costs for the case study area?

Authors also wanted to know what investment is needed to initiate SWC on these remaining sloping croplands as a basis for subsequent SLM improvements. Costs were calculated based on the 50 per cent of the croplands where structures still need to be built (more than 10 million hectares), and arrived at a total cost of 44 billion ETB, or 1.7 billion EUR in August 2014 to cover labour and tools, not including maintenance costs. This amount would have to be invested at the beginning of the 30 year period, either by the government (in areas with high erosion and low NVP) or by the farmers themselves (most areas). The split between costs to the government and in kind costs to farmers according to *Table 20* (above) can be calculated using the ELD Ethiopia Case Study database at the Water and Land Resource Centre (WLRC).

Can sediments in the rivers and hence siltation of reservoirs be reduced?

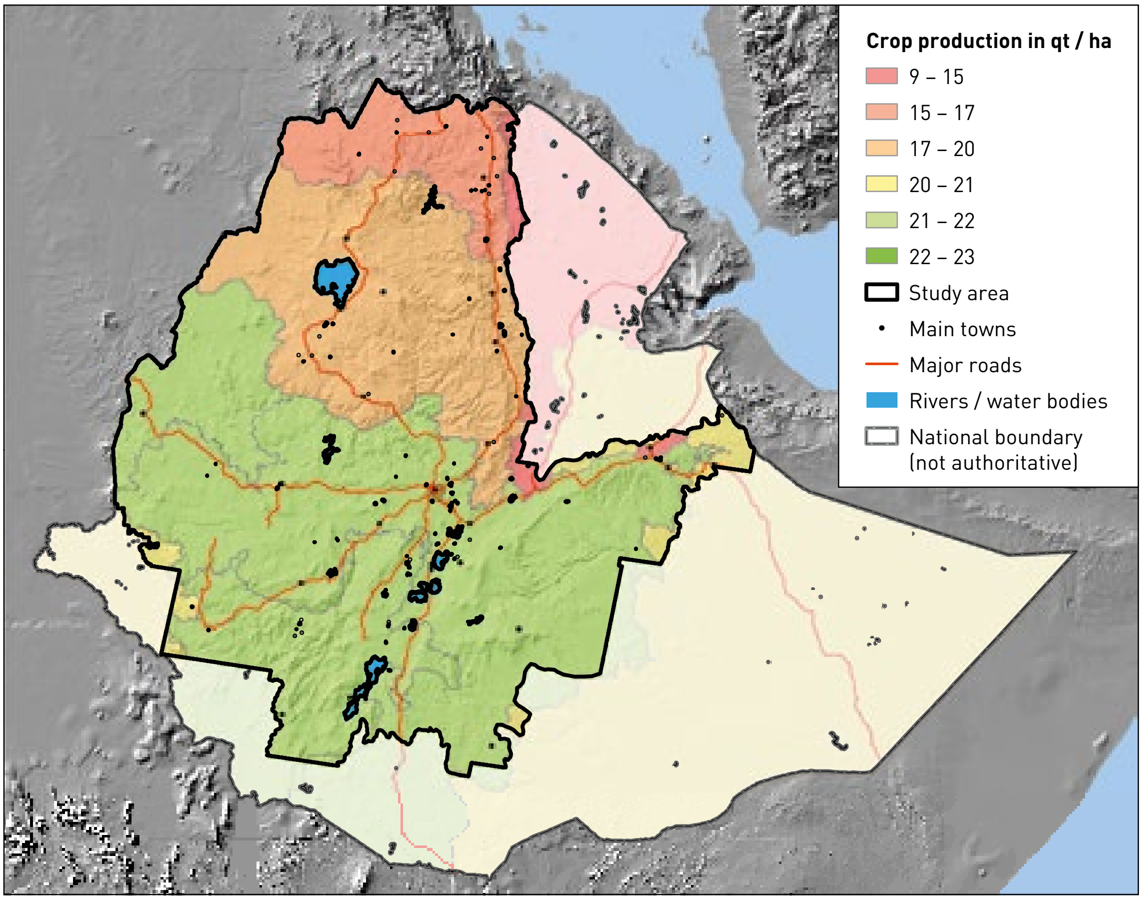
According to the erosion/deposition modelling, the study area has a net loss of about 941 million tonnes of soil sediments/yr. A look at where these sediments originate from reveals the alarming fact that over 50 per cent of all land in the case study area is affected by a net loss of soil. This soil leaves the case study area as suspended sediment in rivers, or is deposited in the inland lakes and smaller wetlands beforehand. The other half of the case study area nevertheless has a positive balance due to sediment accumulation from upslope, meaning that soil lost upslope is deposited downslope before it reaches a river and is carried away as suspended sediment. It would be tempting to conclude that conserving all degrading rainfed cropland would reduce sediment yields in the rivers. This hypothesis is in fact supported by the long-term monitoring observatories of the SCRP, where sediment yields were reduced to about one third of the amounts measured one to two years before conservation structures were built. These catchments, however, are small compared to Ethiopia's larger watersheds, and it is unknown how clearer water running down from conserved lands would perform in terms of eroding river banks. In conclusion, authors refrain from predicting that SLM measures will reduce suspended sediment concentrations in large rivers, although there are strong arguments in support of this hypothesis.

By how much can soil erosion from cropland be reduced?

Looking exclusively at cropland, about 60 per cent of all cropland in the case study area is affected by net erosion, resulting in about 380 million tonnes of sediments per year, or 20 tonnes per ha of cropland per year. Loss of these sediments also entails a huge loss of nutrients (N and P). Assuming that these nutrients need to be replaced by fertilizer to maintain productivity, the cost of nutrient loss alone amounts to 14.4 billion ETB/yr. If all croplands steeper than 8 per cent were conserved, the amount of sediments could be reduced to 222 million tonnes, or 12 tonnes/ha/yr on average, an amount that is very nearly tolerable. This reduction in erosion would also reduce the cost of nutrient loss by 4.55 billion ETB every year.

FIGURE 46

Crop production per region in 2014



What crop improvements can be expected from SLM?

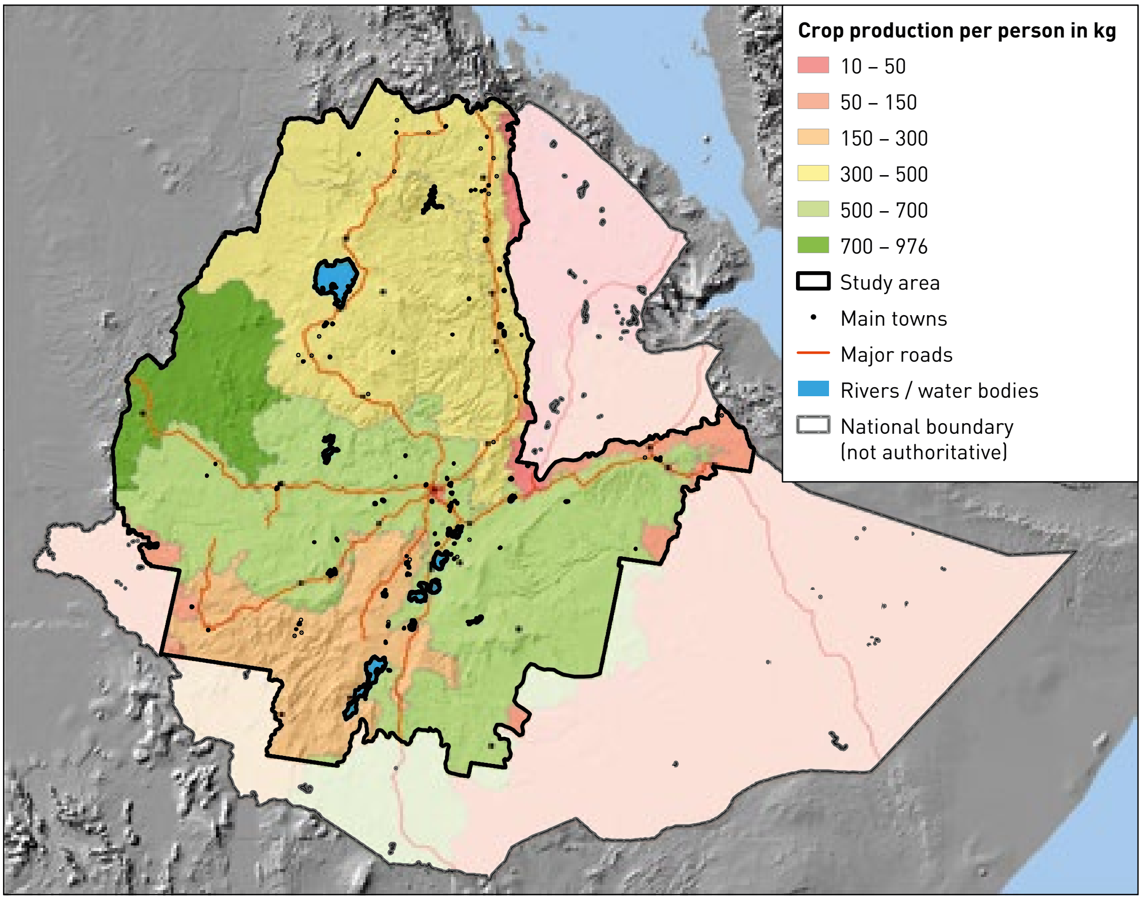
Yields from all croplands were calculated using the crop supply basket model according to agro-ecological zones. They are presented in *Figure 46*.

The results follow the familiar pattern of the Ethiopian Highlands and range from 9 to 23 tonnes/ha/yr, with very low per hectare yields in the dry lowlands towards Afar Region, followed by low yields in the degraded North (Tigray and Amhara Regions), and the highest yields in the western and southern parts of the case study area (Benishangul-Gumuz, Oromia, and SNNP regions). When looking at production per capita, the pattern begins to mix, based on regional population estimates for 2014 (CSA 2007), as shown in *Figure 47*.

Figure 48 shows an improvement for all areas on a tonne/ha/yr basis, although per capita food availability will decrease considerably due to an expected population growth from 90 million in 2014 to 160 million in 2045 (Prizzon & Rogerson 2013). Per capita production in the Tigray, Amhara, and SNNP regions will range between 150 and 300 kg, which is below the level of food self-sufficiency. For pastoralist areas it will be even lower, although it must be acknowledged that the pastoralist diet has not been cereal-based so far

FIGURE 47

Average crop production per capita and region in 2014



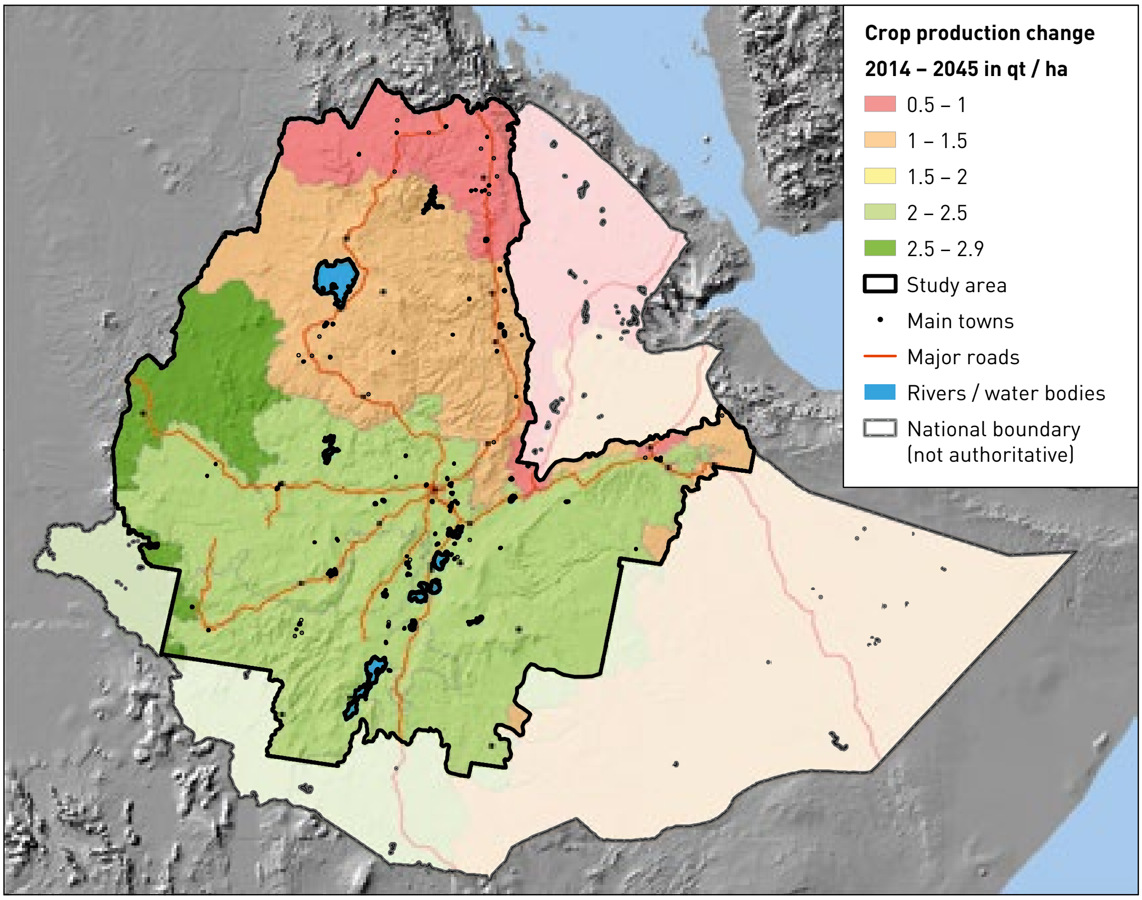
3.3 Sensitivity analysis and internal rate of return at aggregate level

To assess how changes in the costs (labour, tools, and fertilizer) and benefits (crop prices and fodder grass prices) affect the outcome of the study, authors performed a sensitivity analysis at aggregate level. Costs and benefits were aggregated at the wereda level (only for those completely within the study area) and authors performed the CBA while gradually changing the costs and benefits. It is important to note that this aggregation of the costs and benefits at wereda level before performing the CBA can lead to different results when compared to the aggregation of the pixel based data after the CBA (e.g., *Figure 43*). Nevertheless it shows how changes in the costs and benefits affect the outcome like for example the best scenario based on the NPV.

Both costs and benefits were changed at 5 per cent interval from -25 per cent to +25 per cent and the CBA was performed for all combinations of cost and benefit changes. As this was performed for 582 weredas and each scenario, it is not possible to display results here, but results reported for the best scenario (the highest NPV). Interestingly, at this aggregate level for all of the cost and benefit change combinations, only three scenarios showed the highest NPV: Scenario 1.1 ('business as usual', only for one wereda throughout the sensitivity analysis), Scenario 3.2 (conservation structures on all sloping croplands, fodder grass cultivation on all structures, no additional fertilizer), and Scenario 4.2 (conservation structures on all sloping croplands, fodder grass cultivation on all structures, fertilizer everywhere). Depending on the changes in the costs and benefits, the highest NPV was either achieved by Scenario 3.2 or Scenario 4.2. *Table 22* shows selected cost and price change com-

FIGURE 48

Crop production in 2045 for the most intensive scenario (Scenario 4.2), less crop production in 2014



binations and the amount of weredas for the best scenario based on the highest NPV.

The results in *Table 22* indicate that building conservation structures on croplands with slopes > 8 per cent result in the highest NPV even if costs and prices change by +/- 25 per cent. This underlines the fact that investing in conservation structures is likely to be beneficial in the future, even if costs increase and benefits decrease. Additionally it shows that with or without fertilizer use conservation structures are profitable, an important finding considering the volatility of fertilizer prices. Fertilizer can rather be considered as an additional

TABLE 22

Best scenario based on the NPV for selected cost and benefit change combinations

Scenario	Resulting best scenario based on NPV (number of weredas)						
	C: 0% B: 0%	C: +25% B: 0%	C: -25% B: 0%	C: 0% B: +25%	C: 0% B: -25%	C: +25% B: -25%	C: -25% B: +25%
1.1	1	1	1	1	1	1	1
3.2	207	308	114	132	331	408	74
4.2	374	273	467	449	250	173	507

measure to increase income, as it is a recurring yearly investment: Depending on the costs, farmers can choose whether it is worth to buy fertilizer to increase crop yields and thus income, or to cultivate the land without fertilizer, on an annual basis.

In addition to the NPV, the IRR was also calculated for each scenario at aggregate wereda level. The IRR was positive (> 50 per cent) for all weredas and scenarios, and 480 of the 582 weredas showed the highest IRR for Scenario 1.1. This means that the 'business as usual' scenario with few investments (maintenance of existing structures and using fertilizer as currently applied) provides the highest IRR. However, for a subsistence farmer, Scenario 1.1 may not be the most favourable - achieving higher net benefits is likely to be more important than the highest possible IRR. As a result the scenario with the highest NPV is preferable over the scenario with the highest IRR.

This analysis at aggregate level also underlines the importance of spatially explicit, pixel based analyses: Comparing the results in *Table 22* with *Figure 43* shows that some scenarios only became visible' at pixel level. Through the aggregation of costs and benefits at wereda level before performing the CBA, information was lost (Scenarios 1.1, 1.2, and 2.2), which needs to be kept in mind when interpreting the results from the sensitivity analysis.

3.4 Alternative livelihood options

It is beyond doubt that a further doubling of Ethiopia's rural population in the coming 35–45 years cannot be accommodated with the current cropland area unless productivity per hectare is substantially increased. Moreover, natural resources will have to be utilized sustainably. Nevertheless, the current growth rates of the Ethiopian economy indicate that the urban centres will continue to grow dramatically in size and number. While 15 per cent of the population (13.5 million) are living in towns in 2014, this share may increase to 40 per cent (about 60–70 million) by 2045. Alternative livelihoods will develop along the agricultural market chains and outside of them, while small-scale farming might remain the backbone of Ethiopia's rural economy – with similar farm sizes but higher productivity and crop diversity, and on much safer ground due to SLM.

In addition, increasing amounts of land might be developed in the western lowlands, which have so far been unsafe for subsistence farming due to diseases such as malaria, tsetse, yellow fever, and sleeping sickness. Modern and mechanized farming, coupled with some health infrastructure, is currently advancing into these areas (see land cover map, *Figure 4*), and seasonal labour migration from the highlands to lowland areas has become a considerable market for hundreds of thousands of labourers every year.

Food security for Ethiopia as a whole will remain an important issue, as the per capita production is likely to decrease over the next three decades. Importing food to meet the needs would mean a step away from food self-sufficiency. An alternative might be for the mechanized production systems outside small-scale farming to produce more for local markets.

3.5 Policy messages for national and regional levels

The ELD Ethiopia Case Study concludes with six major policy messages that are currently being discussed at the national and regional levels, particularly in regions where soil and water conservation and sustainable land management have already been included in policies and programmes.

Policy message 1: About one third of today's rainfed cropland in Ethiopia does not require immediate action against soil erosion. The other two thirds require conservation structures, in particular all cropland on slopes > 8 per cent. Considerable efforts were made over the past 40 years, and conservation structures are now present on approximately 18 per cent of all cropland. More than 50 per cent of all cropland still needs to be conserved, as 77 per cent of the cropland shows a slope >8 per cent.

Policy message 2: All scenarios included in this report show that the net present value of soil and water conservation measures and their coupled sustainable land management measures is positive at the wereda and higher levels over a 30 year period and at a discount rate of 12.5 per cent. This means they are worth investing in now. However, the assessment hides extreme cases (i.e., small areas or individual pixels) where conservation or sustainable land management cannot be profitable.

Policy message 3: A total of 44 billion Ethiopian Birr (2014) still needs to be invested in soil and water conservation structures in order to conserve all sloping croplands. Half of the cropland can be conserved by the farmers themselves, i.e., without payment for their work; the other half will require support at various levels because the net present value for the farmers may be low, sedimentation of rivers may be high, or both. It is important to make this investment in the next few years before net erosion has reduced crop production too much.

Policy message 4: Nearly 1 billion tonnes of suspended sediments originating from human-induced soil erosion still reach the rivers every year. They silt important reservoirs established for hydropower generation and other purposes, diminishing their functionality. Soil and water conservation is hence also a measure to prolong the life spans of dams and their intended functions.

Policy message 5: There are marked regional differences regarding which scenario is most appropriate. In the Tigray Region, it is best to invest in fodder production along bunds (as much of the croplands are conserved), whereas this would first require extensive soil and water conservation in Amhara Region. In the Oromia Region, the full package of conservation, fodder, and fertilizer is most appropriate. However, these priorities need to be spatially differentiated, which can be done using the ELD Ethiopia Case Study database at the WLRC in Addis Abeba.

Policy message 6: This study did not consider the benefits and costs to society in the cost-benefit analysis (e.g., off-site impacts of soil erosion). Other measures like agronomic changes (e.g., improved crop varieties, plant protection, changes in the farming system, compost application, timely weeding, mulching, expansion of cropland, or other land use types) were also not considered. Through the omission of these additional parameters, it is likely that the benefits were underestimated. Further studies are required to assess the effects of these parameters.

3.6 Conclusion

The data analysed or generated for the present ELD Ethiopia Case Study enabled the detection and characterization of spatial patterns related to LULC, soil degradation, and SLM technologies, as well as the definition of areas with similar clusters of potentials and constraints for SWC and SLM. This was done at a high resolution and covered an impressive area that included most of Ethiopia's rainfed cropland areas. Authors made a new assessment of the extent and magnitude of soil erosion, which also included soil deposition rates downslope and resulting net loss in all rivers originating in the highlands. Recommendations are provided regarding the best scenario for each specific location for the next 30 years, based on economic value. It was not unexpected but certainly satisfying that all scenarios had a positive NPV when compared to business as usual; this means that doing more against soil erosion is better than leaving things the way they are. Recommendation was also given on the amount of investment required to conserve the remaining sloping cultivated lands. The study estimated that a total of 44 billion ETB is required for this task and also shows where direct investment is required and where SWC can be done by farmers themselves.

In conclusion, it should be possible to maintain the current rural population's livelihoods in most areas, but areas are now identified where this will no longer be possible because the resource base cannot be maintained despite even the best interventions. Within agriculture, options can be developed based on the spatial patterns revealed in this study; existing local case studies, expert knowledge, and emerging innovations should also be taken into account. Alternative livelihoods will have to be developed for populations in areas where agriculture is no longer possible, as well as for all rural children that are now growing out of agriculture, and may also no longer have enough land to till. New agricultural areas are being cleared to help maintain food security at the national level, but most people abandoning agriculture will have to find new livelihoods in growing urban and rural centres. Young rural people already tend to migrate to these environments, and this dynamic is likely to increase in the future. The potential impacts of population growth and migration on rural and urban areas and related livelihood options (within and outside of agriculture) need to be considered. Discussion of such options can build on the data and knowledge base, local case studies, and expert knowledge. Additional spatial data such as accessibility – expressed as travel time to larger towns or markets that provide employment – or proximity to locations with a potential for ecotourism should be included as well, however, the availability and applicability of such data still needs to be determined.

In this respect, the framework established in this study enables the financial valuation of land degradation (mainly erosion by water) and different management options and has the potential to be used beyond the current focus on the highland ecosystem's productive function. To date, authors have considered three different management options – conservation structures, fertilizer, and fodder grass – and have shown the potential that such a database has to support informed decision-making and policy formulation. As it is working at the pixel level, the framework is flexible. It can be applied to any given area, and can be updated whenever more accurate data become available. Furthermore, it can be adapted to include more information such as other management options, but also information not related to agriculture. Including these will enable a more holistic assessment of livelihood options in and outside of agriculture. The work performed for the ELD Ethiopia Case Study can therefore be considered as a step towards the ELD Initiative's goal of providing tools for the total economic valuation of land degradation and sustainable land management.

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THE GLOBAL
MECHANISM
UNITED NATIONS CONVENTION
TO COMBAT DESERTIFICATION

For further information and feedback please contact:

ELD Secretariat
Mark Schauer
c/o Deutsche Gesellschaft
für Internationale Zusammenarbeit (GIZ) GmbH
Friedrich-Ebert-Allee 36
53113 Bonn
Germany
T + 49 228 4460-3740
E info@eld-initiative.org
I www.eld-initiative.org

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