UNIVERSITÀ DEGLI STUDI DI TRIESTE
e
UNIVERSITÀ DEGLI STUDI DI UDINE

XXX Ciclo del Dottorato di Ricerca in

Ambiente e Vita

The role of ecosystem services in the spatial assessment of land degradation: a transdisciplinary study in the Ethiopian Great Rift Valley

Settore scientifico-disciplinare: **BIO/07**

DOTTORANDA
Stefania Cerretelli

COORDINATORE
Prof. Giorgio Alberti

SUPERVISORE DI TESI
Prof. Alessandro Peressotti

CO-SUPERVISORE DI TESI
Dott. Alessandro Gimona

ANNO ACCADEMICO 2016/2017

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PhD Student:

Stefania Cerretelli

2016/2017

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ABSTRACT

Land degradation is a widespread problem that affects about 1.5 billion people globally. It can be defined as the decline in the productive capacity of the land, and the loss of functionality of ecosystems. Overall, land degradation leads to ecosystem services degradation, because it affects and causes the depletion of several soil functions (e.g. sediment retention, nutrient cycling, carbon stocks, and water retention). Therefore, it is also a constraint in securing food production and it could cause food insecurity. Hence, land degradation represents a considerable problem especially in developing countries, where people strongly rely on the ecosystems and natural resources for their livelihoods.

The principal aim of this study was to assess land degradation by integrating different sources of knowledges and data, to derive a synthesis relevant to inform decision-making processes, and to target priority areas for conservation and restoration interventions.

In this study, three ecosystem services (ESS) were modelled to infer land degradation in a small area, in the Halaba special *woreda*, located in the Ethiopian Great Rift Valley. In particular, sediment erosion and retention, nutrient retention and export, and carbon storage and sequestration were modelled. Data from a local soil survey, from global coverage datasets, and from a supervised land use cover classification were used for the ESS modelling. Remote Sensing data were used during the parametrisation phase of the ESS modelling.

Local knowledges and perspectives were gathered using an extensive participatory approach that targeted the communities of three *kebeles* in the study area, and the experts of the Halaba *woreda* Agricultural Office. 33 focus group discussions and 32 semi-structured interviews were conducted in the summer 2016.

The information acquired through the ESS modelling and during the participatory approach was then integrated in a Bayesian Belief Network (BBN), a probabilistic graphical model, to derive a spatial explicit land degradation risk assessment.

The results showed that assessing land degradation through the lens of key ecosystem services represents a valid approach. The ESS modelling results showed that the study area is characterised by high soil erosion rates, low carbon storage and sequestration, and low nitrogen retention. Moreover, the ESS modelling also showed that using data from global coverage datasets could affect the reliability of the ESS assessment. Furthermore, the qualitative study, derived from the participatory approach, highlighted the presence of complex linkages between environmental and socio-economic factors, which exacerbate land degradation. The integration of ESS modelling results, participatory approach and literature data in the BBN proved to be an efficient approach to derive a synthesis of the several knowledges acquired during the several steps of this PhD project. Overall, this study demonstrated that a transdisciplinary and interdisciplinary approach is an effective means to address land degradation risks, taking into consideration people needs and priorities.

In order to reverse land degradation trends, there is the need to adopt intense restoration and sustainable land management programs. However, there is also the need to couple conservation interventions with development strategies, such as market access and development, land tenure system improvements, off-farm job opportunities generation, and livelihoods diversification. This could foster land conservation and restoration, and could support sustainable economic growth and inclusive development.

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CHAPTER 1

General Introduction

1. BACKGROUND

Land degradation is a critical and widespread problem that has been increasingly studied in the recent years. It can be defined as the temporary or permanent decline in the biological and economic productive capacity of the land (MEA 2005; UNCCD 2014b). Land degradation can be related to a reduction in ecosystem services provision (MEA 2005; Grainger 2015). According to Lal et al. (2012), land degradation leads to a reduction or complete loss of the biological and economic productivity as well as to a depletion of the complexity of terrestrial ecosystems. It causes the depletion of soil fertility through loss of soil functions such as nutrient recycling, sediment retention, and carbon sequestration, with a consequent reduction in food production (Daily et al. 1997; Bronick and Lal 2005; Lal 2009; Lal 2015a). Moreover, land degradation decreases ecosystem capacity to deliver goods and services, and threatens ecosystem biological and economic resilience capacity and, therefore, the people depending upon natural resources (Oldeman 1992; Lal 1997; MEA 2005; Reed and Stringer 2015; Reed et al. 2015; Sutton et al. 2016). Land degradation can be caused by natural phenomena, by human activities, as well as by a combination of natural degradation reinforced by human actions and impacts (Sundström et al. 2014).

Land degradation incorporates different biophysical and environment factors that individually, or with complex interactions, can affect land productivity and ecosystem functionality. These factors are listed by Gibbs and Salmon (2015) as: salinization, erosion, compaction, desertification, and encroachment of invasive species.

Land degradation poses a considerable threat to agricultural production and to food security (Pimentel 2006; Vlek et al. 2010; Stringer et al. 2011; UNCCD 2012; Amuri 2015; Hillbrand et al. 2017), often leading to a persistent decline in food provision (Daily et al. 1997; Bronick and Lal 2005; MEA 2005; Lal 2009; Lal 2015a). According to UNCCD (2014), half of the global agricultural land has already been degraded. Therefore, there is the need to study and to stop or reverse land degradation drivers and impacts, especially in developing countries where poor people rely upon natural resources and agricultural production for their livelihoods (UNCCD Secretariat 2013; UNCCD 2014a).

Many studies reported that land degradation impacts are exacerbated by the rapid population growth (Grepperud 1996; Mirzabaev et al. 2016) that represents a considerable threat to future food security (Lal 2015a; Lal 2015b). On the other hand, some studies found an opposite linkage between population pressure and land degradation, asserting that higher population pressure combined with socio-economic development could also lead to adoption of sustainable use of resources with reduction and control of land degradation (Bai et al. 2008b; Mirzabaev et al. 2016). Yet, higher population pressure could support implementation of collective actions for sustainable use of natural resources (Gebremedhin et al. 2004), it could trigger technologies development, off-farm activities diversification as well as migration to urban areas (Tiffen et al. 1994; Templeton and Scherr 1999; Nkonya et al. 2016).

Despite the contrasting findings about the connection between degradation and population pressure, it is undeniable that land degradation impacts (e.g. reduction of vegetation cover, depletion of soil fertility, and soil water-holding capacity) have become even more pressing when considering the current trends of the population growth, due to the need of guaranteeing an increasing demand of food production to support more peoples' livelihoods.

The existence of interlinkages between land degradation, biodiversity and climate change was reported by the study of Gisladottir and Stocking (2005) that stressed how controlling and reversing land degradation patterns would also facilitate climate change control, and biodiversity conservation and protection.

However, restoration and conservation processes are often constrained by scarce development or poverty. The link between land degradation and poverty was reported by many studies (Barbier 1997; Barbier 2000; Scherr 2000; The World Bank 2007; Hazell and Wood 2008; Bai et al. 2008b; Barbier 2012; Gerber et al. 2014; Amuri 2015; Hurni et al. 2015; Barbier and Hochard 2016; Gebreselassie et al. 2016). According to Barbier and Hochard (2016), poor rural communities of developing countries living on degraded agricultural land might be secluded from income growth and poverty reduction mechanisms, thus be trapped into a subsistence living strategies. Scherr (2000) stressed that a downward spiral links land degradation and poverty, and vice versa.

Hence, land and ecosystem services degradation exacerbates poverty in developing countries but it also influences human well-being in developed countries (MEA 2005; Bai et al. 2008b; Bai et al. 2013). The linkage between land degradation and people was asserted by Safriel, (2007) as livelihoods as well as well-being directly depend on the highly critical ecosystem services of primary production. Thus, addressing land degradation risk has a central importance especially when trying to link it to the social context of the human well-being derived from use of the ecosystem by people (Safriel 2007).

Barbier (2000) stressed how improper economic policies on export taxes, exchange rates, irrigation schemes, or market prices, could reinforce the link between poverty and land degradation and limiting development and sustainable management strategies and practices (e.g. Barbier 1991; Barbier 1992; Barbier and Thompson 1998).

On the contrary, good policies on market access and prices and on extension and development programs could trigger important investments in long-term conservation practices (e.g. terraces), by securing investments in sustainable management and crop diversification, and by supporting farmers' willingness to invest in new farming technologies and promote farming innovation. In this case, also population growth could reinforce better and sustainable use of the soils (English et al. 1994; Tiffen et al. 1994; Barbier 2000).

Land degradation represents an international concern. During the United Nations Conference on Sustainable Development (Rio+20) hosted in Rio de Janeiro in June 2012, an ambitious goal was stipulated in the outcome document "The Future We Want": achieving a Zero Net Land Degradation (ZNLD). The document stated "the need for urgent action to reverse land degradation. In view of this, we will strive to achieve a land-degradation-neutral world in the context of sustainable development" (United Nations 2012). In order to achieve land degradation neutrality (or ZNLD) by 2030 further land degradation has to be avoided or offset by land restoration. Achieving the ZNLD target would help securing the currently available productive land for present and future generation (UNCCD 2012). Therefore, the ZNLD goal aims i) to address the arrest of further degradation by adopting sustainable land management and ii) to promote restoration and rehabilitation programs to bring back the soil productivity in currently degraded land.

To reverse and control land degradation impacts, there is the need to inform decision-making mechanisms and processes through accurate assessments of land degradation at a global as well as local level. Different studies tried to estimate the extent of the global and/or national land degradation using different indicators and methods (Lal et al. 2012; Gibbs and Salmon 2015). However, according to Gibbs and Salmon (2015), the presence of different definitions of land degradation led to great variance in its estimates at a global level. In fact, many global estimates of land degradation considered just part of the factors linked to land degradation. Furthermore, some studies on land degradation focused only on drylands leading to the difficulty of comparing their results with broader studies that also included temperate or humid habitats (Gibbs and Salmon 2015).

1.1. Global land degradation assessment

The main recent global assessments of land degradation will be described in the following paragraphs.

The UNEP (United Nations Environment Program) commissioned to the International Soil Reference and Information Centre (ISRIC) the Global Assessment of Soil Degradation (GLASOD) to quantify the global distribution of human-induced degradation (Oldeman et al. 1990; Oldeman 1992). The GLASOD was the first attempt to globally map land degradation. The final map of the global land degradation distribution was developed by incorporating the maps and assessments of 21 different regions, developed by 21 different research teams that used the same guidelines to differenciate the severity (e.g. light, moderate, strong or extreme), the type (e.g. water or wind erosion, salinisation, waterlogging, nutrient depletion), the rate, and the causative factors of human-induced soil degradation. The GLADOS estimated that land degradation affected nearly 15% of the total land area. Among the type of human-induced degradation, water erosion affected 56% of the reported degraded land, followed by wind erosion and chemical degradation that affected 28% and 12% of the reported degraded land, respectively. Furthermore, the GLADOS estimated that 38% of the worldwide agricultural land was affected by human-induced soil degradation (Oldeman et al. 1990; Oldeman 1992). The GLASOD map could be useful for determining the severity and extent of the global land degradation distribution, but probably it is not adequate to infer reliable conclusions at a national scale due to the complete dependency upon local experts judgements (Scherr and Yadav 1996; Gibbs and Salmon 2015). By re-interpretering the findings of GLADOS, Bot et al. (2000) found that 65% of the global land has been affected by some degree of land degradation. Dregne and Chou (1992) estimated the distribution of land degradation in the drylands based on expert opinions, research reports, local experiences, and localised data. They estimated that almost 70% of the drylands area has been degraded, reporting that the estention of degradation in irrigated farming lands, rainfed farming lands, and range lands was covering 30%, 47%, and 73% of their total surfaces, respectively.

Another global assessment of land degradagtion was the Global Assessment of Land Degradation and Improvement (GLADA), which measured the land degradation using the NDVI (Normalised Difference Vegetation Index) as a proxy for quantifying the change in the net primary productivity (NPP) (Bai et al. 2008a; Bai et al. 2008b; Bai et al. 2011). The GLADA assessment used NDVI data produced by the Global Inventory Modelling and Mapping Studies (GIMMS), derived from measurements of the Advanced Very High Radiometer (AVHRR). The GLADA found that roughly 24% of the global land has been degraded, of which 18% was croplands, and 43% was forests. The study reported that land degradation directly affected 1.5 billion people worldwide (almost 24% of the entire global population) (Bai et al. 2008a; Bai et al. 2008b; Bai et al. 2011; Bai et al. 2013).

Gibbs and Salmon (2015) converted four global land degradation assessments (e.g. Oldeman 1992; Bai et al. 2008a; Campbell et al. 2008; Bai et al. 2008b; Cai et al. 2011) in one geographically explicit and quantitative framework, and analysed the similarities and discrepancies among the different assessments. The comparison underlined the existence of discrepancies and disagreements especially in certain areas (e.g. Asia, Western Russia, part of South America, Central Africa), mainly due to different definitions, methodologies, time periods and domains in land degradation assessments (Gibbs and Salmon 2015). Therefore, according to these findings, Gibbs and Salmon (2015) pointed out the need to develop and text new approaches that combine innovative satellite data analysis and extensive field data inventories.

Even though land degradation is a globally widespread problem, and despite the discrepancies in estimates of land degradation from different studies, several global assessments found that Africa, and in particular the Sub-Saharan African countries, accounted for the larger area of degraded land at a global scale. Indeed, the GLADOS assessment (Oldeman et al. 1990; Oldeman 1992) found that Africa accounted for more than 40% of the worldwide strongly degraded areas, indicating overgrazing as the most pressing causative factor. The GLADOS assessment also reported that 65% of the African agricultural land has been degraded. The GLADA assessment (Bai et al. 2008a; Bai et al. 2008b) reported that the majority (13%) of the global degraded land was located in the African countries south of the Equator. Dregne and Chou (1992) found in the African drylands percentages of degradation of 18%, 61%, and 74% in irrigate farmland, rainfed cropland, and rangeland, respectively. Moreover, Sub-Saharan African countries were reported accounting for the highest share of the global cost of land degradation (Nkonya et al. 2016).

In Africa, the chemical degradation accounted for 12% of the total degradation, whereas the physical degradation accounted for 4% of the total degradation. Causes of soil degradation in Africa were indicated as overgrazing (49%), agricultural mismanagement (28%), deforestation (14%), and overexploitation of vegetation for domestic and industrial use (13%) (Muchena et al. 2005).

Among the Sub-Saharan Africa, Ethiopia was indicated as one of the mostly affected by land degradation. In fact, the GLADA assessment reported that 26% of Ethiopia has been degraded, estimating that 29% of its population was directly affected by the land degradation (Bai et al. 2008a; Bai et al. 2008b).

1.2. Land degradation in Ethiopia

Land degradation represents a pressing and serious problem in Ethiopia, because of the country's heavy reliance upon natural resources. The agricultural sector, which accounts for over 50% of the Ethiopian GDP, provides livelihoods for over 85% of its population (Shiferaw and Holden 1999; Berry 2003; Bogale et al. 2006). Moreover, in larger areas of Ethiopia, especially drylands, land degradation poses a considerable danger of desertification (Hawando 1997; UNCCD 2012; Grainger 2015).

The harmful impacts of land degradation constitute constraints and hindrances for agricultural development of the poor Ethiopian communities. They face several issues linked to socio-political aspects, geomorphological asset of the country, and weather extreme events (e.g. floods and droughts), which, in the past, have led to severe and destructive famines, such as the 1972/73 and the 1985/86 famines (Hurni et al. 2010; Tesfaye et al. 2014).

Natural resources degradation in Ethiopia has been going on for centuries (Hurni et al. 2010). In the past, social and economic, political and environmental aspects as well as land management aspects played a crucial role in land degradation exacerbation. The interlinkages between different and apparently unconnected aspects have been pointed out by several studies on land degradation in Ethiopia (FAO 1986; Hurni 1993; Desta et al. 2000; Taddese 2001; Tefera et al. 2002; Hagos et al. 2002; Feoli et al. 2002; Berry 2003; Nyssen et al. 2004; Girmay et al. 2008; Gashaw et al. 2014; Amsalu and Mengaw 2014; Hurni et al. 2015). These aspects will be described in the following paragraphs.

Land degradation in Ethiopia has been exacerbated by several direct and indirect aspects. Among the direct drivers of land degradation, several studies reported and acknowledged the importance of past deforestation patterns and trends in degrading large parts of Ethiopia, especially the highlands (Nyssen et al. 2004), as well as the drylands (Hawando 1997). Indeed, deforestation leads to increase of soil erosion, and flooding events, loss of micro-climate regulation, and reduction of organic matter, and overall depletion of soil fertility (Blanco and Lal 2010). Hurni (1993) stressed that, after decades of intense deforestation, the forests were concentrated only on 3% of the country. The current vegetation removal mainly concerned shrubs and trees in between the fields and on steep slopes (Nyssen et al. 2004). Deforestation, together with the abandonment of cropland or the construction of roads, has caused high soil erosion rates that in large parts of Ethiopia have also led to the formation of several gullies (Nyssen et al. 2004; Valentin et al. 2005; Nyssen et al. 2006; Haregeweyn et al. 2015). Clearing of forests, and their conversion into cultivations, has reduced the soil water retention capacity, the soil organic matter, and the nutrient content of soils, mostly through reduced litter production, through changes in soil properties, and through increased erosion rates and decomposition of organic matter by oxidation

(Lemenih and Itanna 2004; Lemenih et al. 2005a; Lemenih et al. 2005b; Girmay et al. 2008; Yimer and Abdelkadir 2011; Mekuria and Aynekulu 2013).

Tadesse et al. (2014) reported that deforestation in the southwestern Ethiopian agroecosystems was an outcome of complex interactions between policy-induced and land-tenure changes, agricultural development schemes and resettlement policies in combination with local socio-economic and cultural practices. Byg et al. (2017) found that deforestation increased because of the population growth, and due to a shift from livestock centred livelihood to farming and crop centred livelihood derived from the change of land tenure system in 1975 (Tsegaye et al. 2010).

The traditional uncontrolled and free grazing system was also indicated as another important driver of land degradation in Ethiopia. Overgrazing has caused changes in the hydrological and biochemical soil proprieties, reduction of vegetation cover and organic input to the soil. Overgrazing caused depletion of soil nutrient content, and increase in soil compaction, which overall have led to lower infiltration rates, higher runoff, and water and wind driven soil erosion (Gebremedhin et al. 2004; Descheemaeker et al. 2006; Girmay et al. 2008; Abdelkadir and Yimer 2011; Mekuria and Aynekulu 2013).

Frequent and traditional soil tillage practice was also reported to adversely affect Ethiopian soil quality (Abdelkadir and Yimer 2011; Ketema and Yimer 2014). In fact, tillage reduces porosity, soil organic matter, soil moisture content, and increases soil compaction and oxidation of organic materials (Bronick and Lal 2005; Lal 2005; Palm et al. 2014).

Furthermore, increase of plot size and short-term increase in agricultural production to enhance household's livelihoods was often obtained by reducing fallowing and increasing mono-cropping practices (Shiferaw and Holden 1999), removing vegetation within the cropland, converting forests and/or marginal areas into cultivated areas (Nyssen et al. 2009; Biazin and Sterk 2013).

Land and soil degradation can also be exacerbated by the habit and necessity of using crop residues and animal dung for domestic use, as fuel and as livestock feeding (Girmay et al. 2008; Haregeweyn et al. 2008; Ketema and Yimer 2014). Yet, the removal of crop residues and the absence of manure application increase runoff effect and erosion, decrease soil water retention, contribute to nutrient and soil organic matter depletion, and microbial biomass reduction (Haregeweyn et al. 2008; Palm et al. 2014).

Although the aforementioned aspects could suggest the necessity of fertiliser and manure application for restoring the soil fertility, their adoption is often constrained by the lack of capacity to purchase the right amount of fertiliser, by the shrinking number of cattle per household for manure production, by the fragmentation or the distance of the plot that makes manure transportation difficult, and by the habit and necessity of using dung as fuel (FAO 1986; Desta et al. 2000; Gebreselassie 2006; Haregeweyn et al. 2008; Girmay et al. 2008; Ketema and Yimer 2014). Concerning farmyard manure, many studies reported that its application was usually limited to the homestead garden farm (Haregeweyn et al. 2008; Girmay et al. 2008), while when used in plot often was not combine with the construction of proper conservation structures for providing better water retention, and for preventing and reducing the soil erosion (Hurni et al. 2015).

The aforementioned direct drivers of land degradation are generally exacerbated by the rapid population growth, that has occurred in Ethiopia over several decades. Ethiopia has reached a total population of about 90-100 million people (African Development Bank Group 2017). It has been estimated that its population grows of about 2 million people per year (FAO and WFP 2010). Due to the high population pressure, it was estimated that 37% of the farming households cultivated less than 0.5 ha, and about 87% cultivated less than 2 ha (FAO and WFP 2010). Therefore, many studies stressed that the population growth is the major indirect cause of soil erosion and land degradation in Ethiopia (Campbell 1991; Hurni 1993; Tekle 1999; Nyssen et al. 2004; Girmay et al. 2008; Kebede et al. 2014; Tadesse et al. 2014; Meseret 2016). The increase in population pressure has led to natural resources exploitation (such as deforestation for cultivation expansion and production of firewood), to removal of crop residues and use of dung as fuel or livestock feeding (Desta et al. 2000; Girmay et al. 2008; Ketema and Yimer 2014), to cultivation expansion in marginal land to cope against the land shortage (Desta et al. 2000). Furthermore, reduction of plot size and land property fragmentation due to the population growth, reduced the farmers' willingness to i) adopt manure, ii) implement conservation measures, and iii) adopt fallowing, rotation and mono-cropping practices, leading to a decline of soil fertility and to land degradation exacerbation (Hagos et al. 2002). Overall, over the past decades, the rapid population growth has led to natural resources overexploitation, overgrazing, deforestation, land mismanagement, mainly to counteract and obviate the shortage of land and the reduction of plot size (Grepperud 1996; Hurni et al. 2005; Lemenih et al. 2014; Zewdie and Csaplovics 2015). During a focus group discussion for a study on land use change drivers, farmers clearly asserted that they increased their cultivated lands size at the expense of woodlands and grassland mainly in response to the increase in their family size (Biazin and Sterk 2013).

In addition, land tenure system and land reforms have also been reported as crucial factors in affecting land management and practices, as well as in determining land use change patterns (Reid et al. 2000; Taddese 2001; Garedew et al. 2009; Byg et al. 2017; Tadesse et al. 2017). Land ownership and property rights are key aspects in order to contribute reversing land degradation and promote efficient use of natural resources and adoption of conservation measures and strategies, as well as foster the adoption of new agricultural technologies (Shiferaw and Holden 1999; Tekle 1999; Gebremedhin et al. 2004; Tadesse et al. 2014). In Ethiopia, the land tenure system, and therefore the bundles of rights associated with it (Schlager and Ostrom 1992), changed many times in the last decades. Before the 1974, during the Imperial regime of Haile Selassie, the land was owned by the Emperor and it was given to the public mainly through a feudal system. The landlords were collecting tributes from the farmers, which had just use right. After the establishment of the military regime, called Derg, in the 1975 the land property was nationalised (Desta et al. 2000; Tefera et al. 2002; Crewett et al. 2008) following the slogan "Land to the Tiller". Use, withdrawal and management rights were given to the farmers. The Derg also established forced villagisation and resettlement programs to promote collectivisation (Hagos et al. 2002). After the overthrow of the military government in the 1991, and with the establishment of the government ruled by the coalition EPRDF (Ethiopian

People's Revolutionary Democratic Front), the rural and urban land remained under public ownership (Tefera et al. 2002). However, the exclusion right was also introduced allowing land leasing for up to 10 years (Hagos et al. 2002).

Therefore, in the last decades, insecure and unclear land property rights and weak land policies were crucial indirect factors in exacerbating land degradation (Taddese 2001; Hagos et al. 2002; Garedew et al. 2009; Tsegaye et al. 2010; Byg et al. 2017). Yet, weak and improper land tenure security was reported as major constraint to promote land investments and farmers' willingness to adopt sustainable natural resources use and land management, and to invest in proper conservation measures and strategies for reversing land degradation trends (Barbier 1997; Shiferaw and Holden 1999; Tekle 1999; Tefera et al. 2002; Gebremedhin et al. 2004; Gebreselassie 2006; Tadesse et al. 2014) and for ensuring human and livelihood security (Bogale et al. 2006). Tefera et al. (2002) claimed that "the higher the security of tenure, the better the level of investment, and the higher the endeavour to maintain or at beast improve the condition of land". Bogale et al. (2006) stressed that "nowhere in Africa has the land issue so intensely and passionately debated as in Ethiopia", and highlighted the crucial role of providing security of land tenure in order to promote a sustainable development to reduce household vulnerability to livelihoods and food insecurity.

Other aspects that indirectly affect land degradation and poverty alleviation are scarce development of the transportation infrastructure, lack or improper market access, lack of rural credit, lack or weakness of participation of rural communities in decision-making processes and strategies, absence of proper policies that support alternative livelihood strategies, and modern farming technologies (Tekle 1999; Shiferaw and Holden 1999; Desta et al. 2000; Tefera et al. 2002; Hagos et al. 2002; Liu et al. 2008; Wossen et al. 2015).

Moreover, improper farming management (such as reduction of fallowing, increase in mono-cropping cultivation), and stagnation of agricultural technology (such as traditional erosive soil tillage practices and traditional plough tools, improver or poor fertiliser application, lack of crop diversification), as well as absence of agricultural intensification and technologies development policies were indicated as causes of the current land degradation patterns in Ethiopia (Nyssen et al. 2004).

Requier-Desjardins et al. (2011) stressed how inappropriate policies, alongside with the lack of finances, were the major constraints to combat land degradation as well as sustain socio-economic development in developing countries.

Development strategies in Ethiopia are therefore constrained by a combination of socio-economic and political aspects, and biophysical and geomorphological factors. Hence, a holistic, interdisciplinary and transdisciplinary study is needed to infer land degradation risk in socio-ecosystems, and to obtain reliable and accurate assessments that could be used to inform local decision-making processes for achieving sustainable development and inclusive growth.

1.3. Study area

The study area is located in the Ethiopian Great Rift Valley, northwest of Hawassa (Fig. 1). It consists of a hydrological subset of several sub-basins of the Bilate River. It contains three small *kebeles* (counties): Andegna Choroko, Laygnaw Arsho, and Asore, where the local survey was concentrated. The area is located in the Halaba special *woreda* (province) (78° 17′N latitude and 38° 06′E longitude), Southern Nations, Nationalities, and Peoples Region (SNNPR). The elevation of the area ranges from 1650 to 2644 m a.s.l.

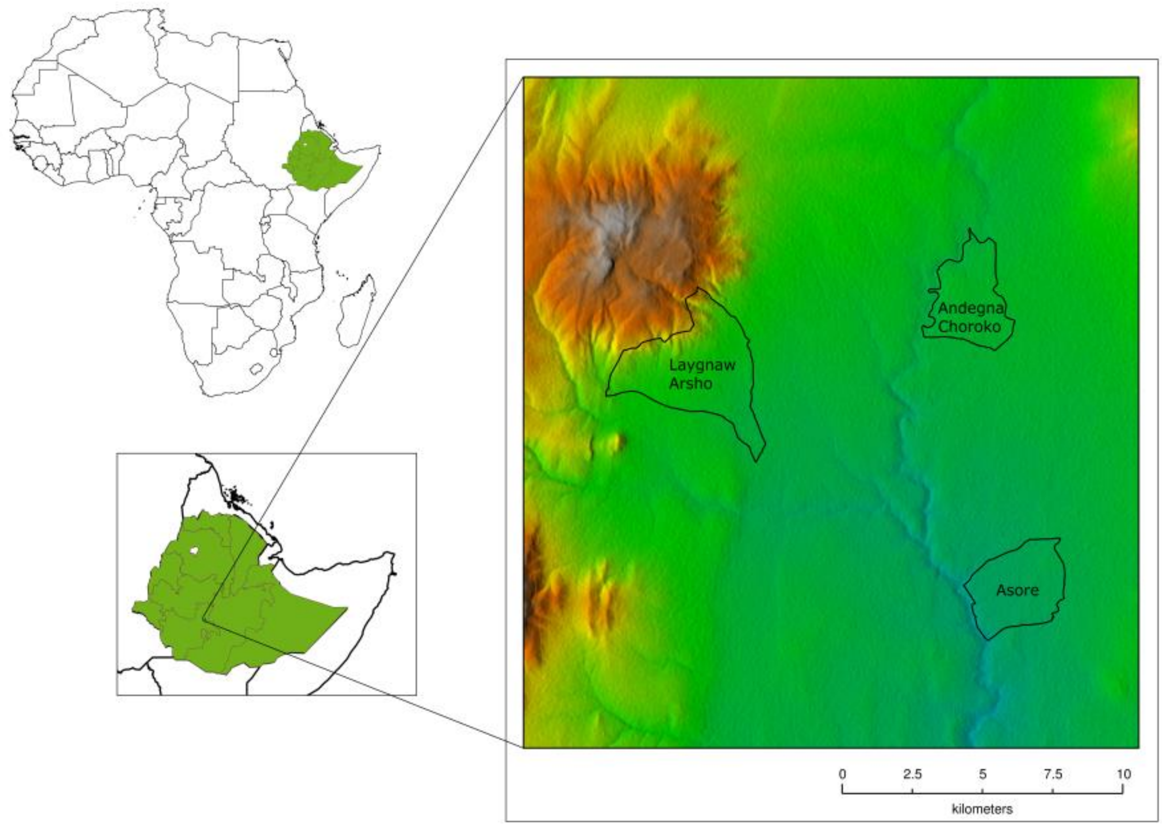

Figure 1. Study area in the Habala special *woreda* (SNNP Region), Ethiopia.

According to the global climatic dataset WorldClim (Fick and Hijmans 2017), the average annual rainfall in the area ranges from 1024 to 1243 mm yr^{-1}, while the average annual temperature varies from 15 to 20 ºC. The area is characterised by a highly seasonal rainfall distribution. The main seasons are: the small rainy season from February/March to May (called *Belg*), the main rainy season from June to September (called *Kiremt*), and the dry season from October to January (called *Bega*) (Fekadu 2015). These seasonal patterns are clearly shown by the Walter and Lieth climatic diagram in Fig. 2 (Walter and Lieth 1960); the vertical pattern shows the humid months, while the dotted pattern shows when the aridity prevails.

Agriculture represents the primary and main activity in the area, and due the average small land per household the crop production is mainly for subsistence (Byg et al. 2017). The principal crops cultivated are maize (*Zea mays*), teff (*Eragrostis tef*), sorghum (*Sorghum bicolor*), haricot bean (variety of the *Phaseolus vulgaris*), millet

(*Elusine coracana*), and some cash crops (e.g. coffee, pepper and khat) with a below average crop yield (CSA 2015a; CSA 2015b; Getnet et al. 2017; Byg et al. 2017). In fact, comparing the data collected from farm households survey in the three *kebeles* (Getnet et al. 2017), and the national average 2014/2015 data (CSA 2015a; CSA 2015b), the area showed a crop yield below the national average. During the 2014/2015 the farmers reported a yield of 1.99 t ha^{-1} for maize, 1.3 t ha^{-1} for sorghum and 1.4 t ha^{-1} for wheat (Getnet et al. 2017), whereas for the same period the national average was 4.4 t ha^{-1}, 2.8 t ha^{-1} and 3.6 t ha^{-1} for maize, sorghum, and wheat, respectively (CSA 2015a; CSA 2015b). The same reports (CSA 2015a; CSA 2015b) indicated an average yield for the SNNP Region of 2.7 t ha^{-1}, 4 t ha^{-1}, and 2.7 t ha^{-1} for maize, sorghum, and wheat, respectively. Therefore, both the national and the regional average yields resulted higher than the yield derived from the sampled farm households of the three *kebeles*.

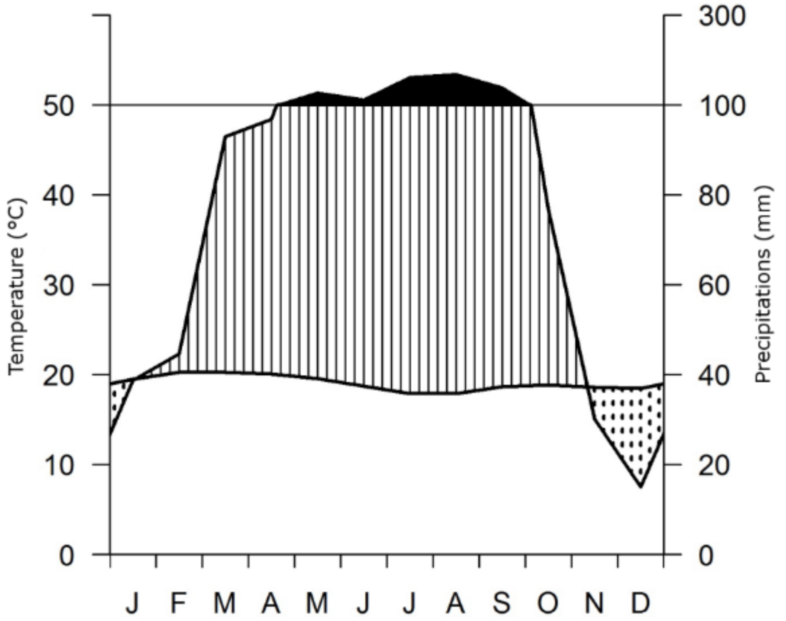

Figure 2. Walter and Lieth climatic diagram of the study area obtained using climatic data from the global dataset WorldClim (Fick and Hijmans 2017).

Land degradation is a serious and pressing problem in the study area, where intense erosion and deep gullies are frequent sights (IPMS 2005; Getnet et al. 2017; Byg et al. 2017). According to the local farmers, the degradation was mainly driven by intense deforestation linked to population growth, and by a shift from livestock to crop based livelihoods. The change in livelihoods strategies was encouraged by the land reform that followed the establishment of the Derg military regime during the 1970s (Byg et al. 2017). Indeed, in the 1975, the new regime launched an intense land redistribution from the former landlords to the tenant farmers, under the slogan “Land to the Tiller”.

Therefore, during the past decades, in order to reduce land degradation, numerous restoration and exclosure areas, dominated by Eucalyptus or Acacia, have been established (IPMS 2005; Yirdaw et al. 2014; Byg et al. 2017). Exclosures are areas where for management, research or restoration purposes, certain animals are excluded or biomass harvesting is controlled. Hence, exclosures are usually established to exclude free grazing practices in order to restore highly degraded sites (Aerts et al. 2009).

Reforestation and afforestation activities and programs started during the Derg regime in the 1980s, after the extreme famines that harmed the whole Ethiopia in the 1972/73 and the 1985/86 (Hurni et al. 2010; Tesfaye et al. 2014). The government and NGOs (Non-Governmental Organisations) supported restoration activities and establishment of exclosures through food for work programmes (Nedessa et al. 2005; Byg et al. 2017). Few communal grazing areas are still present. Most of them were converted into arable lands or restoration areas because of the intense land degradation (IPMS 2005; Byg et al. 2017).

In the Halaba *woreda*, an increment of 22% in population was registered from the 1994 to the 2007, with 38% increase in urban population and 17% increase in rural population (Central Statistical Authority 1996; CSA 2007). The majority of the population is Muslim (around 94%), the rest is Orthodox, Protestant or Christian (Byg et al. 2017).

2. PRINCIPAL AIMS

When trying to address a reduction of land degradation, an approach that might have higher resonance at a global level, as well as a better likelihood of funding could be to indirectly address environmental restoration by instead pursuing other globally pressing issues, such as poverty alleviation and food security (Gisladottir and Stocking 2005).

This was the case of the project ALTER (Alternative Carbon Investments in Ecosystems for Poverty Alleviation), which this PhD project was part of. ALTER was a three years international project funded by ESPA (Ecosystem Services for Poverty Alleviation; *http://www.espa.ac.uk/*), with partners from UK (The James Hutton and the University of Aberdeen), from Ethiopia (University of Hawassa, Southern Agricultural Research Institute (SARI) of Hawassa, and The International Water Management Institute (IWMI) of Addis Ababa), and from Uganda (Carbon Foundation of East Africa) (*http://www.espa-alter.org/*).

ESPA principal aim is to support poverty alleviation and well-being improvements by ensuring better conservation and sustainable management of the ecosystems. More in detail, ESPA aims to support decision-makers and give them the evidence and insight they need to address programs on sustainable ecosystem management and poverty alleviation. These objectives are achieved by supporting and developing innovative and interdisciplinary researches, tools and approaches to enable decision-makers to postulate socio-ecological responses to social, economic, and biophysical trends and patterns.

The ALTER project principal aims were to i) understand the role of soil organic carbon in poverty alleviation, ii) gain better insight into the effectiveness of different investments and management strategies to improve soils quality and fertility, and iii) address how effective investments in soil restoration will promote and safeguard the delivery of ecosystem services that are key to poverty alleviation.

As part of the ALTER project, the work developed for this PhD project aimed to identify the key role of ecosystem services in assessing the land degradation. Ecosystem services represent useful and key indicators of land degradation (Pieri et al. 1995; FAO 2003; Chabrillat 2006; Baldock et al. 2009; Kairis et al. 2014; UNCCD et al. 2016; Tarrasón et al. 2016). However, although ecosystem services modelling represents an effective means for identifying priority areas for restoration and conservation interventions (Duarte et al., 2016; Willemen et al., 2017), studies on ecosystem services are still relative few and usually of limited scope in Africa (e.g. Vihervaara et al. 2010; Seppelt et al. 2011; Wangai et al. 2016).

Land degradation leads to a depletion and loss of ecosystem services (ESS), therefore ESS mapping was used to infer land degradation. A transdisciplinary approach was used in order to address the complexity of the investigated agroecosystem. Geographical Informative System (GIS) and ESS modelling approaches were used, in conjunction with a participatory approach that involved local communities and experts, to assess and estimate ecosystem services and their role in land degradation risk, acknowledging the important role of different levels of local and scientific knowledges for an accurate and local-informative land degradation appraisal.

The specific objectives of this PhD project were to:

- quantify and assess the landscape capacity to supply certain ecosystem services at a local level, integrating data from global datasets, as well as soil properties data from local survey, and a supervised land use classification;
- understand the causes and consequences of land degradation through the engagement of the local communities, in order to gain key local perspective. This is key to obtain accurate and relevant assessments, for addressing effective decision-making processes that aim to promote a local inclusive growth;
- synthesise the knowledges acquired through ESS modelling and from the information acquired during the participatory approach into a novel approach that integrate GIS results and other qualitative and quantitative information in one framework through the probabilistic model Bayesian Belief Network (BBN).

This PhD project aimed to fill the gaps on ESS studies in Africa (e.g. Vihervaara et al. 2010; Seppelt et al. 2011; Wangai et al. 2016), and thus to model ecosystem services for addressing and quantifying land degradation risk. The novel approach presented in this thesis supported the integration of different levels of knowledge to infer land degradation with an interdisciplinary and transdisciplinary approach, that considered important information on biophysical aspects, and socio-economic factors derived from GIS modelling and different sources and levels of knowledges.

To summarise, each thesis Chapter presented a particular aim and in the final research Chapter (5) the knowledges acquired during the previous studies (e.g. ESS modelling, qualitative information derived from the participatory approach) were integrated in one framework in order to achieve and develop a spatial-explicit synthesis of the land degradation risk. In the following Sections the principal aims and key contributions of each research Chapter are reported and briefly described.

2.1. Chapter 2

In the Chapter 2, “Spatial assessment of land degradation through key ecosystem services: the role of globally available data”, ecosystem services modelling was used to infer land degradation risk in the study area.

Land degradation leads to ecosystem services (ESS) degradation because it causes the depletion of several soil functions (MEA 2005; Lal 2009; Lal 2015a). Therefore, the impact of physical factors, in particular soil erodibility and nutrient retention, were modelled at the study area level, to infer land degradation risk.

Soil erosion was identified as one of the major drivers of land degradation worldwide (Lal 1997; Valentin et al. 2005; Pimentel 2006), and in Ethiopia (Hurni 1993; Tamene and Vlek 2008; Adugna et al. 2015; Haregeweyn et al. 2015). Moreover, also nutrient depletion was found causing land degradation globally (Lal 2015a), and in Ethiopia (Haileslassie et al. 2005; Lemenih et al. 2005a). Furthermore, soil erosion as well as nutrient depletion are direct factors in affecting agricultural production and overall food security (Daily et al. 1997; Lal 2009; Gebreselassie et al. 2016). Therefore, accurate and reliable assessment of those ecosystem services and biophysical factors appears to be crucial in order to quantify the study area vulnerability to land degradation. To model soil erosion and retention, and nitrogen retention and export, two different sets of data were established; i) a “global dataset” with data from different global coverage datasets, and ii) a “hybrid dataset” where global data were integrated with data from a soil properties local survey and from a classified land cover map. Through this approach, it was possible to compare the results obtained using the two different sets of data, in order to identify the limitations of using global datasets for modelling at a local scale, and to address possible implications of using different sets of data to inform local decision-making processes. This approach could be useful for identify drawbacks, limitations and advantages in using data from global coverage datasets especially when studying data-poor and remote areas.

To recapitulate, the main objectives of this chapter were to i) assess land degradation through ESS (and in particular soil retention and nitrogen retention) assessment, ii) evaluate the difference in results obtained using different sets of data, and the implications of using global-coverage data in modelling at a local scale. Fig. 3 shows a synthesis of the approach used in this Chapter.

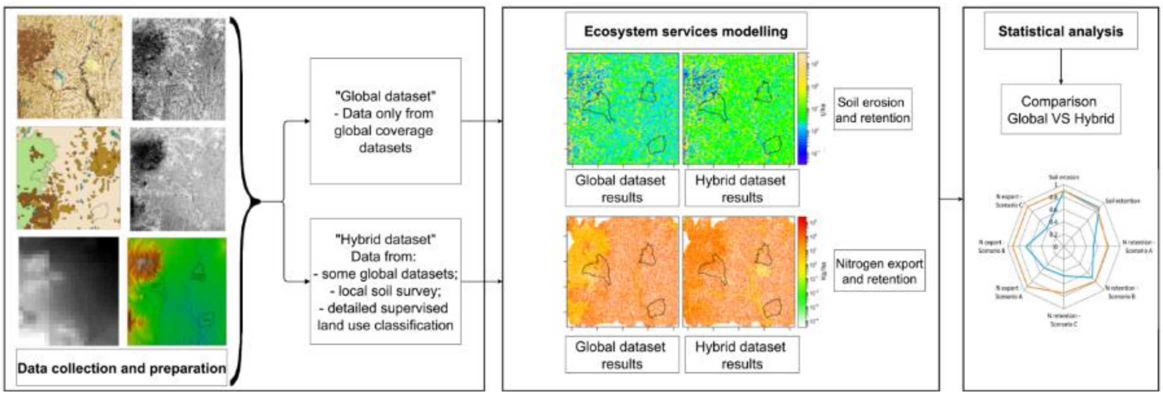

Figure 3. Approach and methodology used in the Chapter 2, “Spatial assessment of land degradation through key ecosystem services: the role of globally available data”.

2.2. Chapter 3

In the Chapter 3, "The implications of modelling carbon storage and sequestration to infer land degradation using globally available data and different scales", the same approach used in the Chapter 2 was presented. In particular, in this study, carbon storage and sequestration was modelled to infer land degradation risk at a local scale.

Carbon stock depletion is closely linked to land degradation patterns. Yet, carbon stocks are crucial both for climate mitigation, by compensating carbon emissions and tackling climate change trends, as well as for restoring soil functions, and fertility (Jobbágy and Jackson 2000; Lal 2004a; Lal 2004b; Lal 2006; Minasny et al. 2017). Initiatives that aimed to increase carbon stock to achieve a sustainable use of the environment have been adopted in the last decades. However, to improve carbon stocks management and to encourage and promote carbon restoration programs and strategies, there is the need to identify priority areas and/or interventions. In fact, decision-making processes rely on mapping and modelling approaches to spatially assess carbon storage and sequestration.

In this study, carbon storage and sequestration was therefore mapped with the overall purpose of inferring land degradation risk at a local level. As for the Chapter 2, in this study two different datasets were used: i) a "global dataset" characterised by data from different readily available global coverage datasets, and ii) a "hybrid dataset" that coupled data from global datasets, soil data derived from a local survey, and land use data derived from supervised classification of satellite images.

The main objectives of this study were to i) assess carbon storage and sequestration keeping in mind its relationship with land degradation and sustainable management, ii) identify possible target areas and interventions to restore the carbon stocks, and iii) identify limitations, advantages and drawbacks of using global data in modelling at a small and local scale.

This approach could help decision-makers to identify possible interventions to reduce land degradation at the study area level, and could emphasise the crucial role of different sets of data in affecting carbon storage and sequestration modelling. The results of this study are key for identifying pros and cons of using global coverage data when modelling in data-poor area and at a small scale.

2.3. Chapter 4

In the Chapter 4, "Using a participatory approach to infer land degradation causes and consequences at different knowledge levels", a participatory approach was used to gain local perspective on land degradation risk, involving the local communities of the three *kebeles* and experts of the Halaba Agricultural Office.

Qualitative approaches and text mining methods were used to gain local knowledge and perspective. These are crucial aspects when trying to support and encourage inclusive development strategies taking into account the needs and the expectations of the local communities and stakeholders (Reed et al. 2007; Reed 2008; Raymond et al. 2010). The developed participatory approach was necessary for inferring land degradation causes and consequences looking at important socio-economic as well as environmental aspects highlighted by the local communities and experts.

An accurate and detailed assessment of land degradation causes and consequences is needed when the study aims to inform decision-making processes for achieving and supporting effective sustainable development and poverty alleviation strategies. This is possible only if participation of local communities is considered and local knowledge is included in the assessment (Reed 2008).

Good and accurate strategies could be unsuccessful if they fail to consider and to acknowledge the needs of local communities that rely on the ecosystem and that are the principal actors in affecting natural resources' use and management.

In this study, a holistic approach was used to take into account different factors, from land management to socio-economic and political aspects that likely affect and exacerbate land degradation risk and local communities' well-being in the study area. Therefore, in the summer 2016 a participatory approach was conducted: several semi-structured single interviews (32) and focus groups discussions (33) were carried out involving households of the communities of the three *kebeles*, and local experts of the Halaba Agricultural Office.

The main objectives of the study presented in Chapter 4 were to: i) identify causes and consequences of land degradation, considering also the harmful impacts of the past and current population growth trends that affected and are still affecting Halaba *woreda*, ii) assess what determine resilience to land degradation and what constraints face the communities for achieving sustainable development and growth, iii) pinpoint possible coping strategies that could help reducing land degradation risk, decreasing climate change vulnerability as well as alleviating poverty.

To conclude, participation of local communities is crucial in order to inform research programs that aim to achieve a better knowledge of the factors in force at a certain landscape level for addressing development and inclusive well-being generation. Cornwall and Jewkes (1995) stressed that "working with the poor and voiceless is infinitely more rewarding that working on them", highlighting the importance of supporting researches that acknowledge the valuable contributions and sources of information that local and poor people could provide.

2.4. Chapter 5

In the Chapter 5, "Spatial Bayesian Belief Networks for mapping land degradation risk", the knowledges acquired during the previous studies were integrated to model land degradation risk using a Bayesian Belief Network modelling approach.

Bayesian Belief Networks (BBNs) are probabilistic graphical models (refer to Chapter 5 for details on BBN modelling methods) that constitute useful tools when trying to integrate qualitative and quantitative data and information, as well as spatial data (e.g. ESS modelling results).

The approach presented in this study represents a novel approach to assess land degradation risk at a local level. BBN modelling constitutes an effective means when trying to synthesise information and data derived from various sources and through different methods. Furthermore, BBN enables an effective communication of the outcomes through a graphical representation that makes the information understandable also for non-modellers and for decision-makers that often lack of technical skills (Cain 2001; McCann et al. 2006). Therefore, BBN modelling could facilitate decision-making processes by making the information more accessible and visually immediate (Gonzalez-Redin et al. 2016). Accordingly, in this study, using a novel approach that integrates GIS and BBN modelling, it was possible to map the land degradation risk, therefore obtaining a spatial-explicit land degradation risk assessment that could represent an effective means for identifying priority areas and measures for targeting restoration and sustainable interventions.

To summarise, the main objectives of this study were to i) map land degradation risk by integrating different sources of knowledges (e.g. ESS modelling, qualitative information), ii) highlight trends of land degradation in different and plausible land use scenarios derived from literature reviews and from local knowledge acquired during the participatory approach, iii) identify targeting areas for restoration interventions implementation, and iv) suggest effective measures and interventions for reducing land degradation and supporting inclusive development strategies.

The Chapter 5 represented the synthesis of the knowledges presented in the previous Chapters. This approach enabled the integration of different levels of knowledge and/or information and data (ESS modelling results, local communities and local expert knowledges) to achieve a transdisciplinary land degradation risk assessment that integrated the main results obtained in the previous studies.

To conclude and recapitulate, the overall contribution of the Chapter 5 was to show the effectiveness of the novel GIS-linked Bayesian Belief Network tools, that enabled a spatial BBN modelling for synthesising different knowledges and integrating several data sources.

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CHAPTER 2

Spatial assessment of land degradation through key ecosystem services: the role of globally available data[1]

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Authors: Stefania Cerretelli[*,a,b,c], Laura Poggio[a], Alessandro Gimona[a], Getahun Yakob[d], Shiferaw Boke[d], Mulugeta Habte[d], Malcolm Coull[a], Alessandro Peressotti[b], Helaina Black[a]

* Corresponding author, [a] The James Hutton Institute (United Kingdom), [b] University of Udine (Italy), [c] University of Trieste (Italy), [d] Southern Agricultural Research Institute (Ethiopia)

1. INTRODUCTION

Soil erosion is strongly associated to land degradation in Ethiopia (Tamene and Vlek 2008; Adugna et al. 2015; Haregeweyn et al. 2015) and worldwide (Oldeman 1992; Lal 1997; Valentin et al. 2005). In Ethiopia soil formation is reported to range from 2 to 22 tons (t) ha^{-1} yr^{-1} (Hurni 1983; FAO 1986), while several studies estimated soil loss by erosion in the range of 0 to 500 t ha^{-1} yr^{-1}. The large range identified depends on the high heterogeneity of the Ethiopian landscape where several aspects are involved (e.g. geomorphology, weather conditions, management practices, soil types) (FAO 1986; Hurni 1993; Herweg and Ludi 1999; Bewket and Sterk 2003; Bewket and Teferi 2009; Brhane and Mekonen 2009; Haile and Fetene 2012; Amsalu and Mengaw 2014; Ali and Hagos 2016).

Land degradation, soil erosion and land use also affect soil nutrient composition (Bewket and Stroosnijder 2003; Lemenih et al. 2004; Haileslassie et al. 2005; Girmay et al. 2009), through reducing soil depth and declining soil fertility (Lal 2015), with adverse effects on the productive capacity of the land. Girmay et al. (2009) estimated sediment-associated nutrient losses by runoff of 2.1–32.8 kg $ha^{-1}yr^{-1}$ for N, 0.02–0.2 kg $ha^{-1}yr^{-1}$ for available P, and 0.35–5.25 kg $ha^{-1}yr^{-1}$ for available K, with higher loss in cultivated land and lower loss in exclosures. Haileslassie et al. (2005) reported nutrient losses through soil erosion of 79 kg N ha^{-1} yr^{-1}, 15 kg P ha^{-1} yr^{-1} and 50 kg K ha^{-1} yr^{-1}. Bewket and Stroosnijder (2003) found that soil total nitrogen (N) content showed variation among land use types as well as due to differences in climatic factors, erosion and leaching intensities, soil texture, soil organic matter (SOM) content, grazing and cultivation intensity, and crop type.

Erosion and nutrient depletion are very important and widely used land degradation indicators (Pieri et al. 1995; Syers et al. 2002; FAO 2003; Chabrillat 2006; Martín-Fernández and Martínez-Núñez 2011; Kairis et al. 2014). Given their association with ecosystem functions, areas where soil and nutrient retention services are low could be targets for ecosystem restoration, and this in turn has been shown to improve the level of the indicator services. For example, Mekuria and Aynekulu (2013) found an increase of 28-38% for the total soil N stock and of 26-39% for the available P stock after the restoration of degraded grazing lands into exclosures.

Ecosystem services modelling is an important tool to identify priority areas for intervention (Duarte et al., 2016; Willemen et al., 2017) that can improve the soil's functional state (Lal 2015). Several tools and approaches have been developed to assess and map ESS, as indicated by a number of reviews (e.g. Bagstad et al. 2013; Turner et al. 2016; Pandeya et al. 2016) that highlight the high variability of ESS with spatial and temporal scale. Reviews of ESS by Seppelt et al. (2011) and Vihervaara et al. (2010) found few ecosystem services studies for Africa, while Wangai et al. (2016) found an increasing number of studies. Nonetheless, studies are still relatively few and of limited scope. One of the barriers is the unavailability of high resolution local data (e.g. Liu et al. 2008). Bai et al. (2013) stressed the importance of good quality climatic, soil and land use information in order to obtain robust assessment of the benefits from ecosystem services. The absence of up-to-date land cover datasets at national level represents another challenge (Hurni et al. 2015).

The use of different datasets at different spatial scales and extents is an important topic in different disciplines and in mapping environmental properties (Poggio et al. 2010; Grunwald et al. 2011; Malone et al. 2013; Malone et al. 2017). In this respect, the modifiable areal unit problem (MAUP) underlines the importance of the scale problem and of the aggregation (or zoning) problem in the spatial analysis (Openshaw and Taylor 1979; Jelinski and Wu 1996). Therefore, the results dependency on the spatial resolution and extent was often indicated by studies on environmental factors and properties, digital soil mapping, as well as species richness and distribution (Sobieraj et al. 2004; Foddy 2004; Rahbek 2005; Cavazzi et al. 2013). Grêt-Regamey et al. (2014) studied the effect of scale on ESS mapping and found substantial differences between the fine and coarse resolution analyses especially when local heterogeneity, which is scale dependent, was important. This is corroborated by the results of Verhagen et al. (2016) who found that heterogeneity is often important when mapping different ecosystem services. However, to the best of my knowledge, this comparison has not yet been modelled with reference to the limitations of globally available data sets, in particular for soil and nutrient retention modelling. Therefore, this work aimed to investigate the differences in results due to the use of globally available data sets instead of a better local alternative, and importantly, whether different management or intervention decisions would be taken. The objectives of this study were to:

- compare modelling results (soil retention and nutrient retention) obtained using different sets of data, one using only data from global datasets, and the other integrating the global data with information from a local survey, and evaluate how much the results differ at spatial level;
- evaluate the extent of land degradation assessing two ecosystem services: i) soil retention ability and ii) nutrient (nitrogen) retention ability, using a GIS and remote sensing approach;
- identify possible consequences, advantages, and limitations in assessing ecosystem services using different scales of resolution.

2. DATASETS

2.1. Data sources

In this study, two different sets of data were used to provide model inputs (see Table 1). A "global dataset" included data available from global geographic databases and a "hybrid dataset" which integrated global data with information from a local survey carried out during 2015. The two datasets were chosen to identify possible differences in the modelling results derived from using different inputs data. The two datasets differed by data availability, resolution and extent, cost and time of data collection and preparation). Remote sensing data were derived from Landsat, MODIS (Moderate Resolution Imaging Spectroradiometer), Sentinel 1 and Sentinel 2 sensors, elevation data from SRTM (Shuttle Radar Topography Mission), climatic data (e.g. precipitation) from WorldClim dataset, and soil properties data from ISRIC (International Soil Reference and information Centre) SoilGrids 250m dataset (see Appendix A for further details).

Table 1. Description of global and hybrid datasets. In brackets are reported the units of the input variables and their resolution in global and hybrid datasets.

ESS models	Input variables	Global dataset	Hybrid dataset
Soil erosion and retention modelling	Rainfall erosivity factor (R factor) (MJ mm ha^{-1} h^{-1} yr^{-1})	- WordClim Precipitations (~1 km)	- WordClim Precipitations (~1 km)
	Soil erodibility factor (K factor) (Mg h ha MJ^{-1} mm^{-1} ha^{-1})	- ISRIC; soil texture and organic matter content (250 m)	- Local samples; soil texture and organic matter content (25 m)
	Slope length and steepness factor (LS factor)	- SRTM (30 m)	- SRTM (30 m)
	Cover and management factor (C factor) (0-1)	- Landsat NDVI (30 m)	- Landsat NDVI (30 m)
	Support practice factor (P factor) (0-1)	- set to 1	- Manual digitalisation
Nutrient retention and export modelling	Elevation (m)	- SRTM DEM (30 m)	- SRTM DEM (30 m)
	Root restricting layer depth (mm)	- ISRIC (250 m)	- ISRIC (250 m)
	Plant available water content (AWC) (fraction content, 0-1)	- ISRIC; AWC (250 m)	- Local samples; water at FC and at WP (25 m)
	Average annual precipitation (mm)	- WordClim; monthly precipitation (~1 km)	- WordClim; monthly precipitation (~1 km)
	Average annual potential evapotranspiration (mm)	- MODIS; evapotraspiration (~1 km)	- MODIS; evapotranspiration (~1 km)
	Land use cover	- GLNC land cover (300 m)	- Local land cover from supervised classification (30 m); Covariates: Sentinel 2, Landsat
	Watersheds	- SRTM (30 m)	- SRTM (30 m)
	Root depth (mm)	- ISRIC (250 m) - Land cover from GLNC (300 m)	- ISRIC (250 m) - Land cover from supervised classification (30 m)
	Evapotranspiration coefficient	- Landsat NDVI (30 m) - Land cover from GLNC (300 m)	- Landsat NDVI (30 m) - Land cover from supervised classification (30 m)
	Nutrient loading (kg ha^{-1} yr^{-1})	- Literature - Land cover from GLNC (300 m)	- Literature - Land cover from supervised classification (30 m)
	Vegetation filtering capacity	- Literature - Land cover from GLNC (300 m)	- Literature Land cover from supervised classification (30 m)

2.1.1. Global land use

The FAO Land Cover of Ethiopia map derived from the Global Land Cover Network (GLNC) (Arino et al. 2008; FAO 2009; Arino et al. 2010) was used for the global dataset (*http://www.fao.org/geonetwork/srv/en/main.home*).

Table 2 shows the global land use classes' description and an approximate correspondence with the local land cover classes (see for comparison Table 3).

Table 2. Global land use classes' description. See Table 3 for corresponding global land use classes' description.

Global LU Class	Corresponding local LU class	Description	Area in %
14	5	rainfed cropland	54.6
20	3	mosaic cropland (50-70%)/vegetation (grassland/shrubland/forest) (20-50%)	17.1
30	2	mosaic vegetation (grassland/shrubland/forest) (50-70%)/ cropland (20-50%)	7.7
60	1	open (15-40%) broadleaved deciduous forest/woodland (>5m)	0.1
110	NA	mosaic forest or shrubland (50-70%)/grassland (20-50%)	0.9
130	NA	closed to open (15%) shrubland (<5m)	19.6
150	NA	sparse (<15%) vegetation-sparse woody vegetation/herbaceous sparse vegetation.	0.2

2.2. Local survey

Local soil data were derived from samples collected during a local survey carried out in 2015 (Black et al. 2015). Totally 354 samples were collected for 20 cm of soil depth from: i) different fields of 75 selected households in the three *kebeles*; ii) 108 semi-natural sites and farmland sites and iii) 6 restoration sites of different ages.

In this study, the 354 samples collected for 20 cm of soil depth and representative of different environment (e.g. forests, woodland, farmland, degraded land) were used for the following data: soil organic carbon percentage, bulk density, soil texture (sand, silt and clay content), soil water at field capacity and soil water at wilting point (see Section 3.2 for details on local soil data maps generation). The samples were analysed following standard international ISO methods (see Appendix A for details on soil data analysis methods).

3. METHODS

The procedure used to model sediment erosion and retention and nitrogen retention and export, and analyse the obtained results is highlighted in Fig. 1 in which three main steps are indicated: i) data collection to derive the “global” and the “hybrid” datasets; ii) sediment erosion and retention modelling, and nitrogen retention and export modelling using the two different datasets; iii) statistical analysis to compare the modelling results and highlight the differences obtained using different sets of data (global and hybrid datasets).

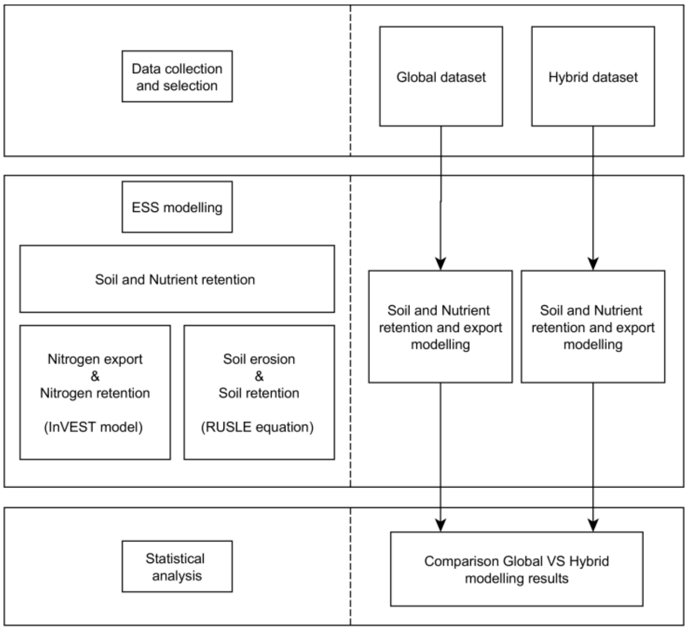

Figure 1. Flowchart. The left side shows the main general steps of the methods used in this study (data collection, ESS modelling, and statistical analysis). The right side shows the separate steps for both the two datasets (global and hybrid) used.

3.1. Local land use

The local land use dataset was derived using a two-step supervised classification. The local land use classification obtained using a classification and regression trees approach (namely RandomForest; Breiman 2001) was subsequently visually verified and manually modified, through digitising of polygons and labelling, using Google Earth® images as background (see Appendix A for further details). Table 3 reports the classes’ description and characterisation.

The two land use classifications are different. The local land use classification has more details and the land use classes are better defined and more homogeneous. The supervised classification and the subsequent manual digitalisation (see Appendix A) enables to identify classes that are not reported in the global land use classification (e.g. settlements areas and degraded land), which are important land use classes to model ecosystem services. On the contrary, the global land use cover presented classes described as shrublands that were not identified in the local land use classification.

Table 3. Local land use classes' description. See Table 2 for corresponding global land use classes' description.

Class Local LU	Corresponding global LU class	Description	Area in %
1	60	Forests and exclosures in the riverplain	2.5
2	30	Forests and farmland in hilly area (mixed semi-natural and agricultural areas)	13.4
3	20	Settlements and farmland alongside settlements	18.7
4	NA	Degraded land	9.5
5	14	Farmland	53.0
6	NA	Halaba, bigger villages and paved streets	1.5
7	NA	Riverine areas	0.6
9	NA	Grassland, graze land	0.8

3.2. Soil properties data

ISRIC soil data (soil organic carbon percentage content, soil texture, AWC) were used in the global modelling. The data for the first 20 cm of ISRIC soil organic carbon percentage ($SOC_{\%}$), soil texture (sand, silt and clay), and plant available water (AWC) were obtained using the trapezoidal formula as indicated by Hengl et al. (2017). For further details on data preparation see Appendix A. Plant available water (AWC) is defined as the difference between water content at field capacity (FC) and water content at permanent wilting point (WP) (Kirkham 2014). In this case it was derived with a FC of pF 2.3 (Hengl et al. 2017).

Local soil properties maps were obtained through an interpolation process using an extension of the scorpan-kriging approach (McBratney et al. 2003), i.e. hybrid geostatistical Generalized Additive Models (GAM; Wood 2006), combining GAM with kriging (Poggio and Gimona 2014; Poggio and Gimona 2017). A prediction grid of 25 m x 25 m resolution for the first 20 cm of depth was obtained (see Appendix A for details).

3.3. Ecosystem services modelling

3.3.1. Soil erosion and retention modelling

The factors used in the equation USLE (Universal Soil Loss Equation) (Wischmeier and Smith 1965) and RUSLE (Revised USLE) (Renard et al. 1991; Renard et al. 1997; Panagos et al. 2015a; Panagos et al. 2015b; Ballabio et al. 2017) were used to estimate average annual soil loss:

$$A = R \times K \times LS \times C \times P \quad (1)$$

where:

A = average potential soil loss (t ha^{-1} yr^{-1})

R = rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1})

K = soil erodibility factor (Mg h ha MJ^{-1} mm^{-1} ha^{-1})

LS = slope length and steepness factor.

C = cover and management factor

P = support practice factor. The P factor was set to 1 in the whole area for the global dataset whereas for the hybrid dataset polygons characterised by two categories of soil and water conservation (SWC) measures were identified and digitalised: i) restoration areas with terraces and afforestation practices, and ii) cultivation areas in terraces assigning P values of 0.5 and 0.6, respectively, based on other studies for Ethiopia (Hurni 1985; Eweg et al. 1998; Haregeweyn et al. 2013) (for the P factor map see Appendix A).

Subsequently soil retention was computed using the following equation (Tallis et al. 2013; Leh et al. 2013):

$$SR = RKLS - A \tag{2}$$

where:

SR = soil retained (t ha^{-1} yr^{-1})

$RKLS$ = maximum potential soil loss which assumes the landscape is bare (t ha^{-1} yr^{-1}) obtained multiplying R, K and LS factors.

Rainfall erosivity factor (R factor)

The R factor was calculated using the equation in Renard and Freimund (1994) that considers the Modified Fournier Index (MFI) a good approximation of the R factor (Arnoldus 1977):

$$MFI = \sum_{i=1}^{n} \frac{p_i^2}{P} \tag{3}$$

$$\mathrm{R} = 0.7397 \times \mathrm{MFI}^{1.847} \text{ for MFI<55 mm} \tag{4}$$

$$\mathrm{R} = 95.77 - 6.081 \times \mathrm{MFI} + 0.4770 \times \mathrm{MFI}^2 \text{ for MFI>55 mm} \tag{5}$$

where:

MFI = Modified Fournier index (mm)

p_i = average monthly precipitation (mm)

P = average annual precipitation (mm)

R = rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1})

The aforementioned R factor equations were chosen, among other equations (e.g.: Renard and Freimund 1994; Panagos et al. 2015b; Ballabio et al. 2017), due to the lack of information of intensity, kinetic energy and duration of erosive rainfall events, necessary to calculate the R factor using other methods. This approach was also used by other Ethiopian studies (Meshesha et al. 2015; Ostovari et al. 2017; Fenta et al. 2017).

Erodibility factor (K factor)

The K factor was calculated using the following equations:

$$K = 0.0293(0.65 - D_g + 0.24D_g^2) \cdot exp\left\{-0.0021\frac{OM}{C} - 0.00037\left(\frac{OM}{C}\right)^2 - 4.02C + 1.72C^2\right\} \quad (6)$$

where:

K = soil erodibility factor (Mg h ha MJ^{-1} mm^{-1} ha^{-1}) (Torri et al. 1997; Torri et al. 2002).

OM = percentage of organic matter

C = fraction of clay content.

D_g = logarithm of the geometric mean of the particle-size distribution, simplified formula (Borselli et al. 2009) derived from Shirazi et al. (1988). With CL, SL, SA = percentage of clay, silt and sand.

$$D_g = \frac{-3.5CL - 2.0SL - 0.5SA}{100} \quad (7)$$

Slope length and steepness factor (LS factor)

The LS factor (Smith and Wischmeier 1957; Wischmeier and Smith 1978) was calculated using the equations implemented by GRASS GIS (Weltz et al. 1987) that reflect the estimated intensity of rill to interrill erosion and the presence of erosion associated with thawing soil:

$$LS = \left(\frac{\lambda}{72.6}\right)^m (10.0\,sin\,\theta + 0.027) \quad for\ s \leq 8\% \quad (8)$$

$$LS = \left(\frac{\lambda}{72.6}\right)^m (17.2\,sin\,\theta - 0.55) \quad for\ s \geq 8\% \quad (9)$$

where:

LS = slope length and steepness factor (LS topographic factor)

λ = horizontal projection of a slope *s* = slope in percent

m = slope lengths exponent calculated as the ratio β of rill erosion (caused by shear of flow) to interrill erosion (caused primarily by raindrop impact):

$$m = \frac{\beta}{1 + \beta} \tag{10}$$

and

$$\beta = \left[\frac{E\left(\frac{r}{i}\right)\left(\frac{\sin\theta}{0.0896}\right)}{\frac{0.79}{(2.96 \sin\theta + 0.56)}} \right] \tag{11}$$

sin θ = slope angle

E(r/i) = ratio of rill to interill erosion (Weltz et al. 1987).

Cover management factor (C factor)

The C factor was derived from the Normalised Difference vegetation Index (NDVI) as van der Knijff et al. (1999, 2000):

$$C = exp\left[-2 \cdot \frac{NDVI}{(1 - NDVI)}\right] \tag{12}$$

3.3.2. Nutrient retention and export modelling

The data needed by the nutrient model of InVEST (InVEST 3.2.0, Nutrient Retention: Water Purification; *https://www.naturalcapitalproject.org/invest/*; Sharp et al., 2015) are summarised in Table 1. The InVEST tool requires look-up tables for each land use class. In case of spatial data (i.e. root depth and evapotranspiration coefficient) zonal statistics were calculated to obtain mean values for each land use class. Nitrogen (N) loading for each land use class in kg ha^{-1} yr^{-1} were derived from literature based on the land use classes characterisation (see Table 4 for further details).

Three different scenarios were implemented using different loading quantities: A) low loading (half of the recommended rate of Diammonium Phosphate (DAP) and UREA and low farmyard manure (FYM) application as indicated by Getnet et al. (2017)); B) medium loading (recommended rate of DAP and UREA and low FYM application as indicated by Getnet et al. (2017)) and C) high loading (recommended rate of DAP and UREA and double FYM application compared to scenarios A and B).

Table 5 shows the loading scenarios and the vegetation filtering efficiency per land use class.

Table 4. Look-up table of data used in the nutrient modelling.

Input data	Sources	Explanation details
Root depth (mm)	ISRIC	Root restricting layer depth used as proxy
Plant evapotranspiration coefficient (Kc)	Mutiibwa and Irmak (2013)	$Kc = 1.58 \times NDVI - 0.111$ (13)
Nutrient loading (kg ha^{-1} yr^{-1})		
- Inorganic fertiliser	Getnet et al. (2017)	From DAP and UREA that contain approximately 18% and 46% of Nitrogen (USDA 2008; IPNI 2010a; IPNI 2010b).
- Atmospheric deposition	Galy-Lacaux and Delon (2014)	Nitrogen loading derived from atmospheric deposition.
- Organic fertiliser	Getnet et al. (2017); Haileslassie et al. (2005)	Farmyard manure (FYM), that contains approximately 16 g N per kg of FYM (Lupwayi et al. 2000).
Vegetation filtering efficiency	Leh et al. (2013); Smil (1999)	Capacity of vegetation to retain nutrient as a fraction content of the amount of nutrient flowing into a cell from upslope (Sharp et al. 2015).

Table 5. Scenarios (Sc) of N loading and vegetation filtering efficiency (VFE) by land use class.

		Sc A (N load in kg ha^{-1} yr^{-1})	Sc B (N load in kg ha^{-1} yr^{-1})	Sc C (N load in kg ha^{-1} yr^{-1})	VFE
Global land use class	14	26.975	46.45	46.45	0.5
	20	77.55	79.6	147.6	0.6
	30	31.7	39.9	55.9	0.65
	60	7.5	7.5	7.5	0.72
	110	7.5	7.5	7.5	0.7
	130	7.5	7.5	7.5	0.65
	150	7.5	7.5	7.5	0.6
Local land use class	1	7.5	7.5	7.5	0.75
	2	31.7	39.9	55.9	0.65
	3	77.55	79.6	147.6	0.6
	4	15.7	23.9	23.9	0.3
	5	26.975	46.45	46.45	0.5
	6	7.5	7.5	7.5	0.05
	7	7.5	7.5	7.5	0.02
	9	7.5	7.5	7.5	0.6

3.4. Statistical analysis

Because of the different resolutions of the input data, each input map was resampled using a nearest neighbour resampling algorithm at 250 m and at 30 m for the global and the hybrid dataset, respectively. The results of the hybrid modelling were subsequently resampled at 250 m resolution using a nearest neighbour resampling algorithm for comparing the two sets of results. The ESS modelling results were summarised at sub-catchment scale using mean, median, sum zonal statistics. Linear regression models were used to compare the results obtained using the global or the hybrid datasets at both pixel and sub-catchment resolution. The results were also compared using a rank analysis correlation, a test for association between paired samples, using the Kendall correlation coefficient. R^2 of the linear regression models and rank correlation coefficient both at pixel and at sub-catchment level were then shown through a spider graph. The comparison was for the same model to test the impacts of different data inputs at different scales.

3.5. Software used

I used Quantum GIS and GRASS GIS open source software (GRASS Development Team 2017; Quantum GIS Development Team 2017) and the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST, version 3.2.0) tool (Sharp et al. 2015), Nutrient Retention: Water Purification. InVEST is a tool for modelling several ecosystem services. It can be used to inform decisions based on mapping results of key ecosystem services (for further details see Appendix A) and InVEST 3.2.0 documentation available at: *https://www.naturalcapitalproject.org/invest/*).

R CRAN (R Core Team 2017) open source software was used for the statistical analysis, in particular the following packages were used: “raster” (Hijmans 2015), “rgrass7” (Bivand 2015), “rasterVis” (Perpiñán-Lamigueiro and Hijmans 2013).

4. RESULTS

The results obtained with the two datasets were compared in Fig. 2. These statistical results were obtained by regressing the results of the global modelling against the results of the hybrid modelling for all the ESS models (sediment erosion and retention, and nitrogen retention and export) and for the different loading scenarios of the nitrogen modelling. Fig. 2 shows the R^2 of the linear regression models (in blue) and the coefficient of the rank correlation analysis (in orange) at pixel resolution (a) and at catchment (b) resolution. The spider graphs (Fig. 2) show that the correlation among the two sets of results is good if rank correlation analysis is considered both at pixel (a) and at catchment (b) resolution. The R^2 of the linear model show lower correlation between the two sets of results especially at pixel level. Detailed description is provided in the following sections; soil erosion and retention modelling results (Section 4.1), and nutrient retention and export modelling results (Section 4.2).

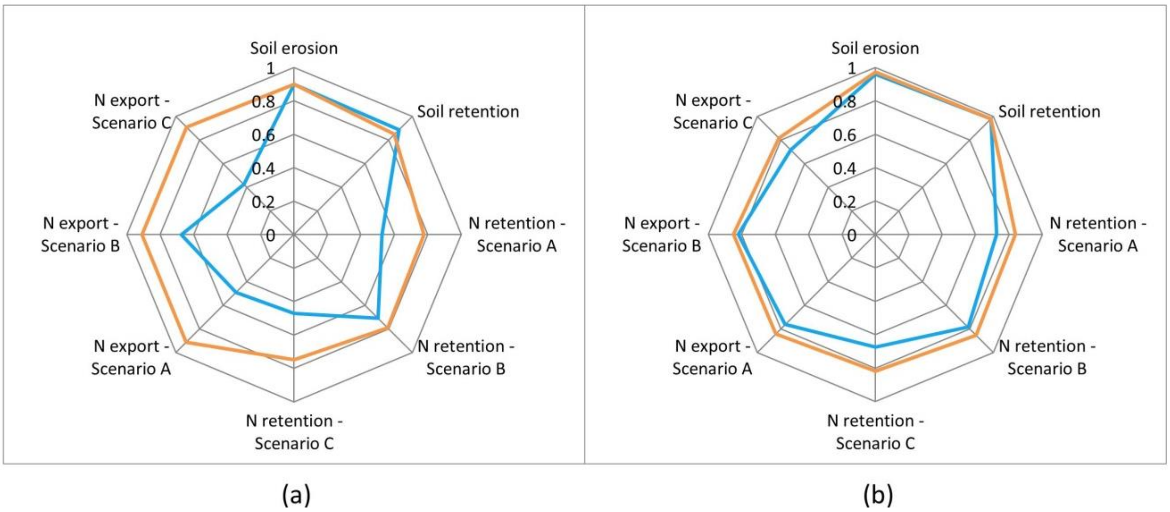

Figure 2. Spider representation of R^2 of linear model (in blue) and rank correlation coefficient (in orange) at pixel resolution (a) and at sub-catchment resolution (b) between the global and the hybrid modelling results.

4.1. Soil erosion and retention modelling

Most of the layers used in the soil erosion and retention modelling were common between the global and the hybrid datasets. K and P factors were the two different input layers. The K factor of the hybrid dataset was derived using the local soil survey data. The P factor used in the hybrid modelling was derived from the detailed local land use map. On the contrary, for the global dataset, the K factor was derived using ISRIC data, whereas the P factor was set to 1 (see Table 1 for details).

The soil erosion ranged from 0.1 to 1129 t ha^{-1} with a median of 2.3 t ha^{-1}, and from 0 to 2228 t ha^{-1} with a median of 3.6 t ha^{-1} in the global and the hybrid modelling, respectively. The maps of the annual soil erosion per pixel are shown in Fig. 3, while Fig. 4 shows the annual soil erosion amount at sub-catchment level (t yr^{-1}). The two maps show that the hybrid modelling estimated higher potential soil erosion.

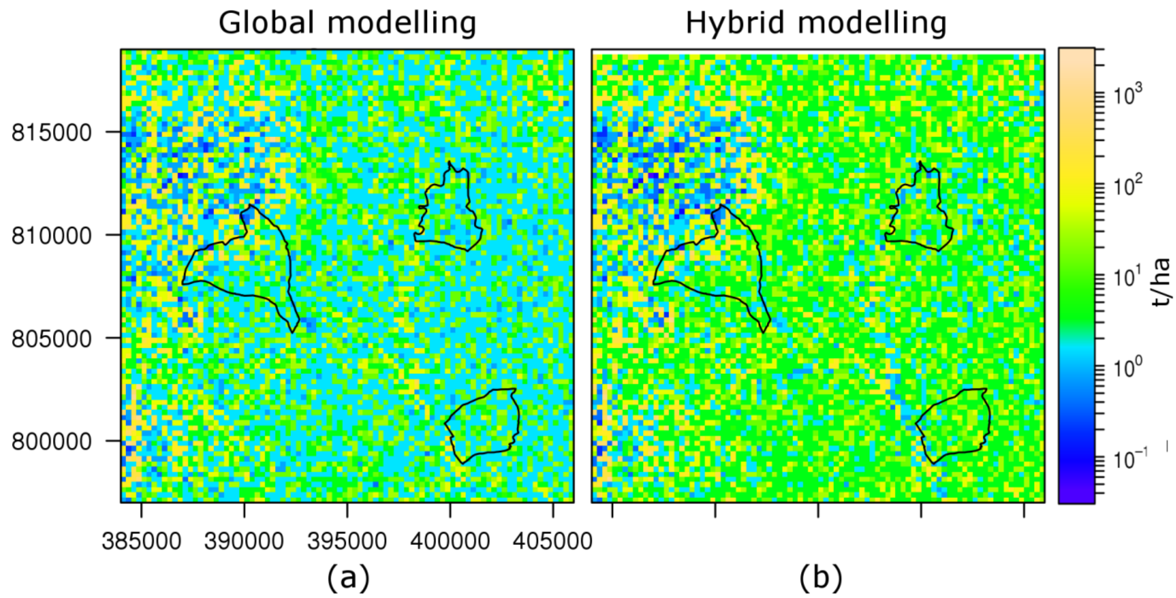

Figure 3. Soil erosion (t ha^{-1} yr^{-1}) in the global (a) and the hybrid (b) modelling.

The linear regression model between global and hybrid modelling results showed good correlation both at pixel level and at sub-catchment level with a R^2 of 0.898 and 0.958, respectively. The rank correlation analysis showed a good correlation with correlation coefficients of 0.897 and 0.972 at pixel and sub-catchments resolution, respectively (see Fig. 2).

Fig. 5 shows the histograms of the median value of soil erosion (t ha^{-1} yr^{-1}) per global (5a) and local (5b) land use classes. In blue are shown the results obtained using the global dataset, while in green are shown the results obtained using the hybrid dataset. Histograms in Fig. 5 highlight the better differentiation among land use classes obtained using the hybrid dataset. In histogram of Fig. 5b the class with higher median soil erosion rate (t ha^{-1} yr^{-1}) was the number 7, which consists of riverine areas and that represents the lower distribution among the eight local land use classes. High median soil erosion estimates were found also in the class number 4 (degraded land). Overall, Fig. 5 shows that hybrid modelling estimated higher mean and median annual soil erosion compared to the global modelling. Finally, the similar spatial distribution showed in Fig. 3 and Fig. 4 is also confirmed at land use class level. In fact, the histograms in Fig. 5 show similar soil erosion patterns per global (Fig. 5a) and local (Fig. 5b) land use classes using the global (blue bars) or the hybrid (green bars) datasets.

Table 6 shows soil erosion rates per range categories for both the global and the hybrid. In approximately 60% of the area, in both the global and the hybrid modelling, the soil erosion rate ranged between 0 and 5 t ha^{-1} yr^{-1}. In the remaining 40% of the area the soil erosion rate ranged mainly between 5 and 500 t ha^{-1} yr^{-1} with percentages that slightly differed among the global and the hybrid modelling. The very high soil erosion rates (50-500 t ha^{-1} yr^{-1}) represented 9.4% and 12.8% of the whole area in the global and in the hybrid modelling, respectively. They characterised steep areas, most of them already highly degraded, as well as river banks where bigger restoration efforts have been given in the past years. Extreme erosion rates were associated with higher slope length gradient (LS factor) and they were limited to small areas in the western hills.

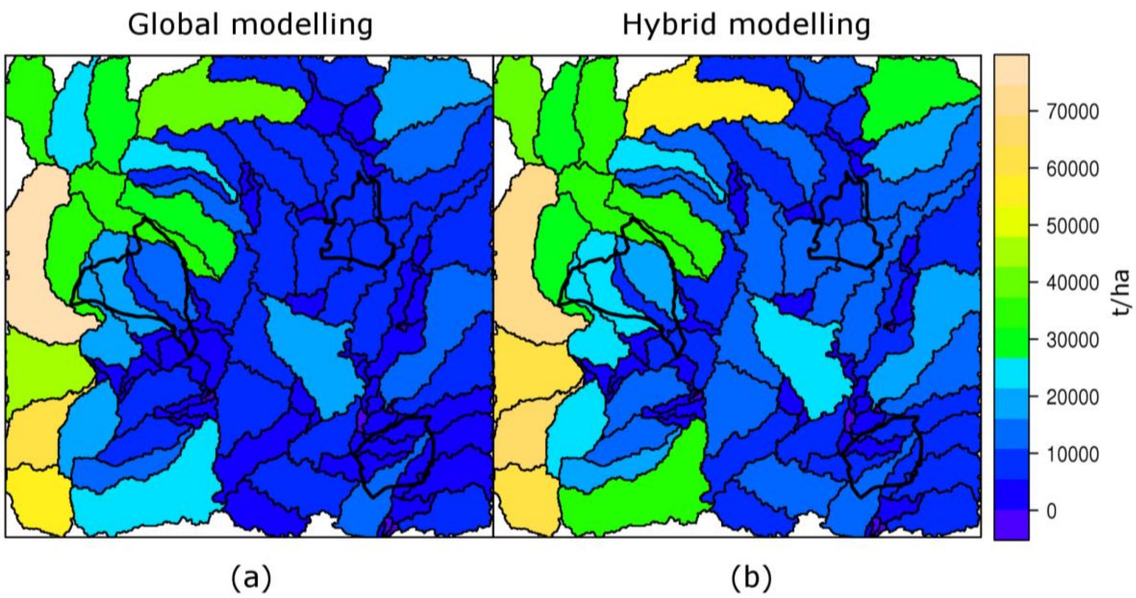

Figure 4. Sub-catchment distribution of total soil erosion (t yr^{-1}) in the global (a) and the hybrid (b) modelling.

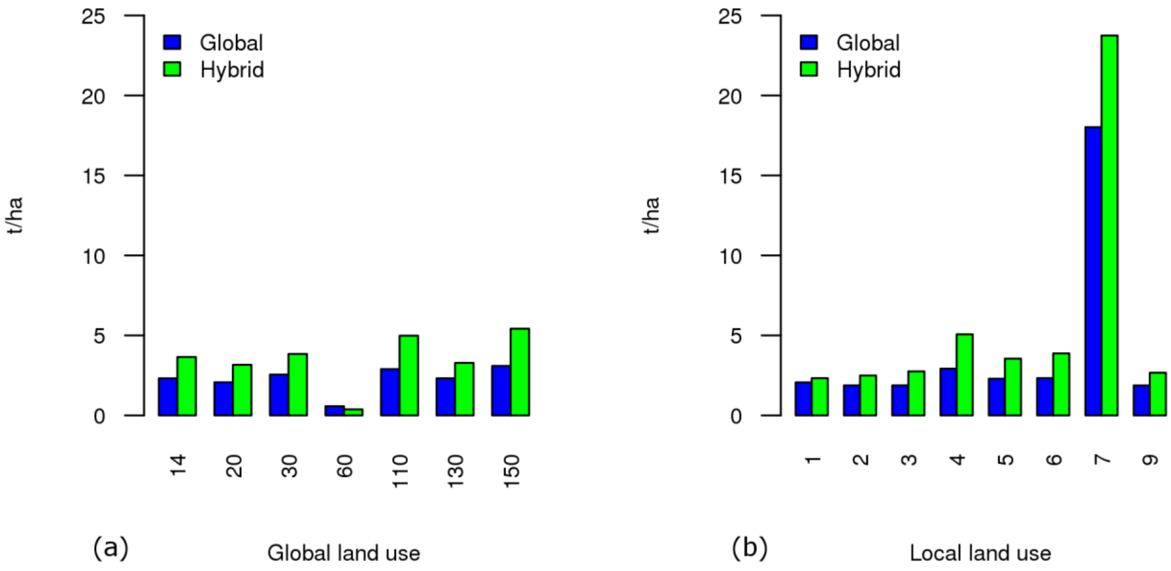

Figure 5. Histograms of median soil erosion (t ha^{-1} yr^{-1}) per global (a) and local (b) land use classes. The results obtained in the global modelling are represented in blue, while the results obtained in the hybrid modelling are in green.

Table 6. Soil erosion rates in the study area in both the global and the hybrid modelling results.

Soil erosion rate (t ha^{-1} yr^{-1})	Erosion potential	Global modelling results		Hybrid modelling results	
		Area in km^2	Area in %	Area in km^2	Area in %
0-5	Low	293.94	60.7	287.91	60.3
5-10	Moderate	19.13	4.0	9.63	2.0
10-50	High	124.63	25.7	117.22	24.5
50-500	Very high	45.31	9.4	61.07	12.8
500-1500	Extreme	1	0.2	1.12	0.2
>1500	Extremely high	-	-	0.03	0.006

The annual soil retention ranged from 1 to 2975 t ha^{-1} yr^{-1} with a median of 3.6 t ha^{-1} yr^{-1} and from 0 to 5121 t ha^{-1} yr^{-1} with a median of 5 t ha^{-1} yr^{-1} for the global and the hybrid modelling results, respectively. Global and hybrid modelling results showed similar soil retention spatial distribution as shown in Fig. 6. Fig. 6 shows that the areas with higher soil retention rate were situated in the western part of the study area in both the global and the hybrid modelling.

The statistical analysis showed similar results to the soil erosion modelling. The correlation was good especially at sub-catchment level with rank correlation coefficient of 0.979, while at pixel level the rank correlation coefficient decreased to 0.847 (see Fig. 2). The regression analysis showed a high correlation both at pixel (R^2 0.887) and at sub-catchment (R^2 0.977) level.

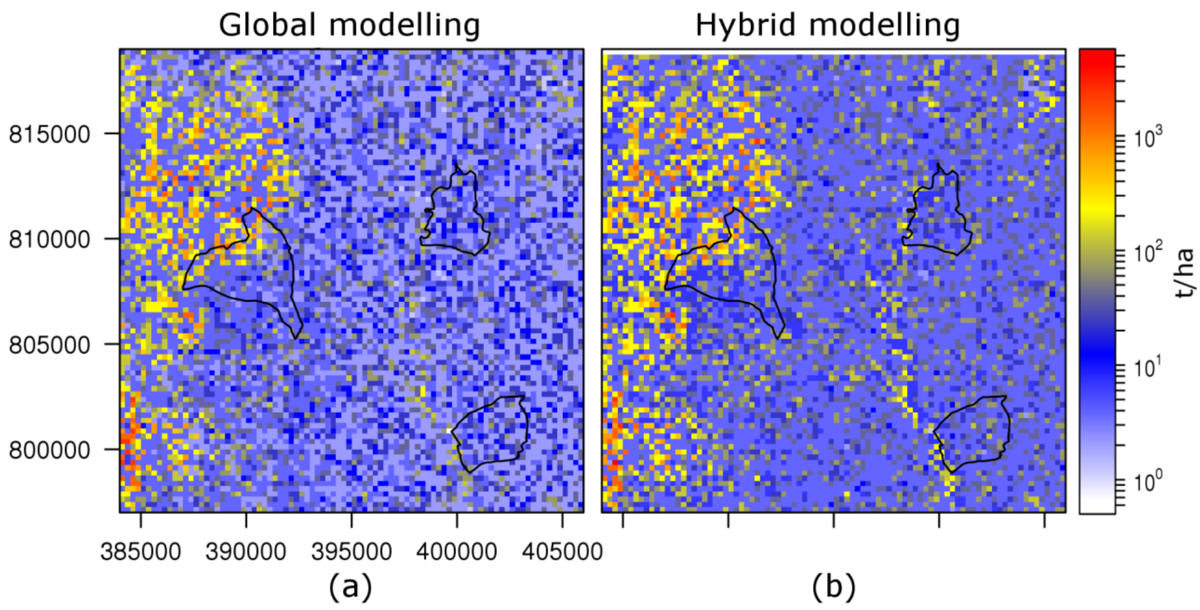

Figure 6. Soil retention (t ha^{-1} yr^{-1}): global (a) and hybrid (b) modelling results.

4.2. Nutrient retention and export modelling

4.2.1. Nitrogen retention modelling

The nitrogen retention results are an indication on how much nitrogen load is absorbed by each pixel and the total amount of nitrogen retained at sub-catchment level.

The median N retention for the whole area in the scenarios A, B and C was 9.21, 10.83 and 11.06 kg N ha^{-1} yr^{-1} in the global modelling and 12.70, 20.14 and 21.09 kg N ha^{-1} yr^{-1} in the hybrid modelling. While the mean nitrogen retention in the whole area in the scenario A, B and C was approximately 30, 41 and 53 kg ha^{-1} yr^{-1} in the global modelling and 32, 44 and 58 kg ha^{-1} yr^{-1} in the hybrid modelling.

The R^2 of the linear models analysis for the three scenarios ranged from 0.47 to 0.71 and from 0.67 to 0.78 at pixel and sub-catchment level, respectively (see Fig. 2). The higher R^2 was estimated by the linear model between global and hybrid modelling of the scenario B both at pixel and at sub-catchment level. The rank correlation analysis showed good correlation with rank coefficient that ranged in the three scenarios from 0.75 to 0.79 and from 0.82 to 0.85 at pixel and at sub-catchment resolution, respectively.

The three scenarios showed very similar spatial distributions therefore only the results for scenario C (high N loading) are shown and further discussed.

Fig. 7 shows the spatial distribution of the global and hybrid nitrogen retention modelling results in the scenario C. The main differences on spatial distribution between global and hybrid modelling results were located especially in the western part of the area where the nitrogen retention was higher in the hybrid modelling. The spatial pattern at sub-catchment level (Fig. 8) confirmed that the hybrid modelling estimated higher nitrogen retention compared to the global modelling especially in the western hilly area.

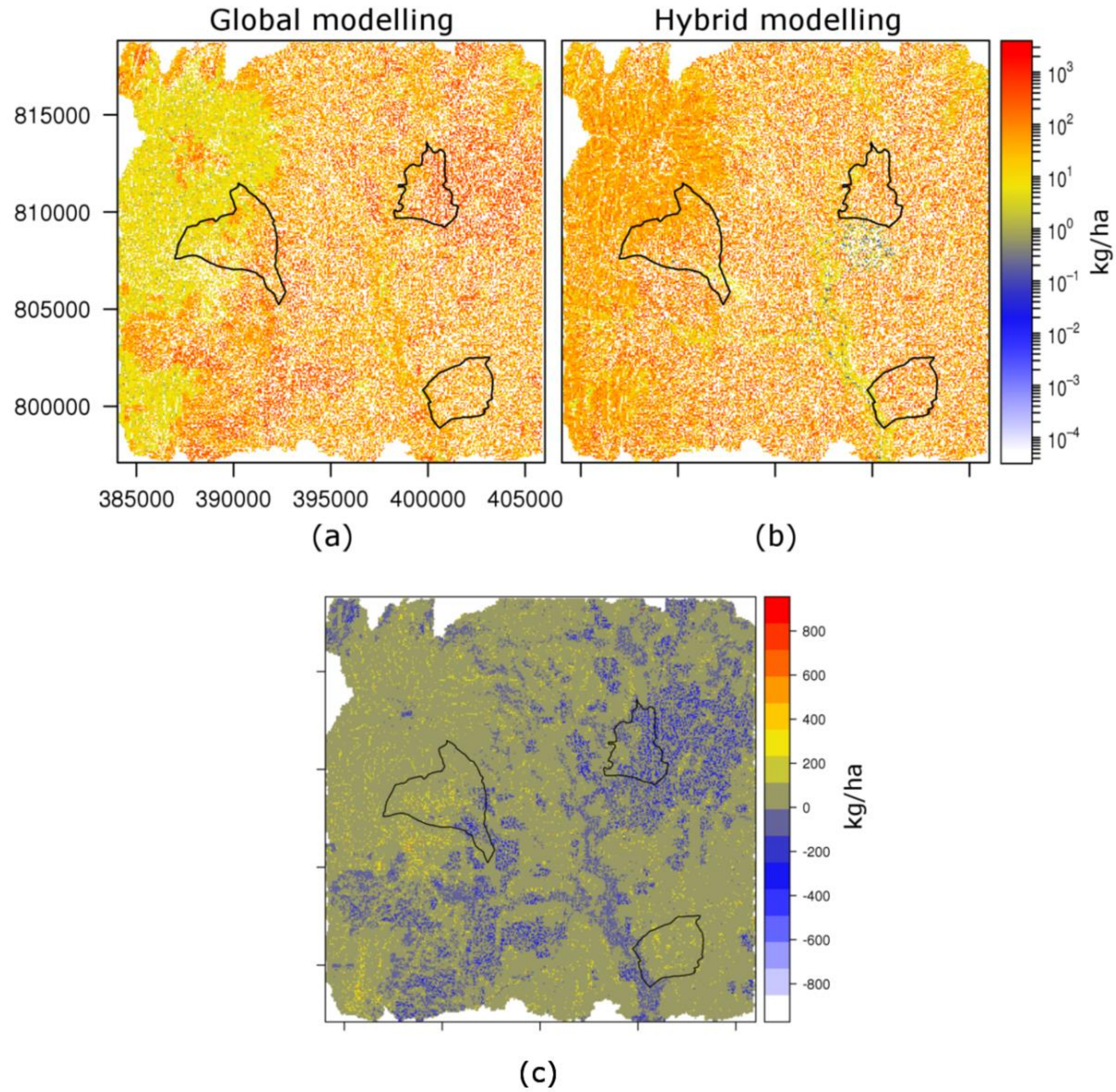

Figure 7. Spatial distribution of nitrogen retention in the global (a) and the hybrid (b) modelling, and their differences (c) in kg ha^{-1}.

Fig. 9 shows the histograms of the median value of nitrogen retention (kg ha^{-1}) of the scenario C for global (9a) and for local (9b) land use classes. In blue are shown the results obtained using the global dataset and in green are represented the results obtained using the hybrid dataset. Considering the global result per global land use classes, the classes with higher N retention were the numbers 20, 30 and 14, mosaic cropland with semi-natural vegetation, mosaic vegetation with cropland and rainfed cropland, respectively. While in the hybrid modelling at local land use classes level higher N retention were obtained in the classes 2, 3 and 5, forest and farmland in the hilly area, settlements and farmland alongside settlements and farmland, respectively.

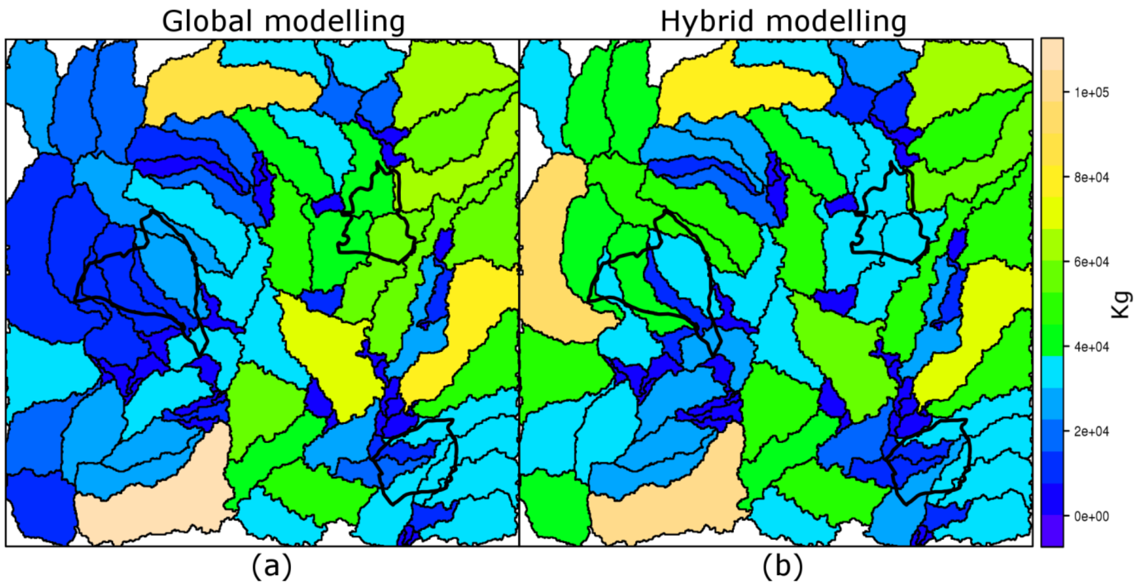

Figure 8. Nitrogen retention at sub-catchment resolution in the global (a) and the hybrid (b) modelling.

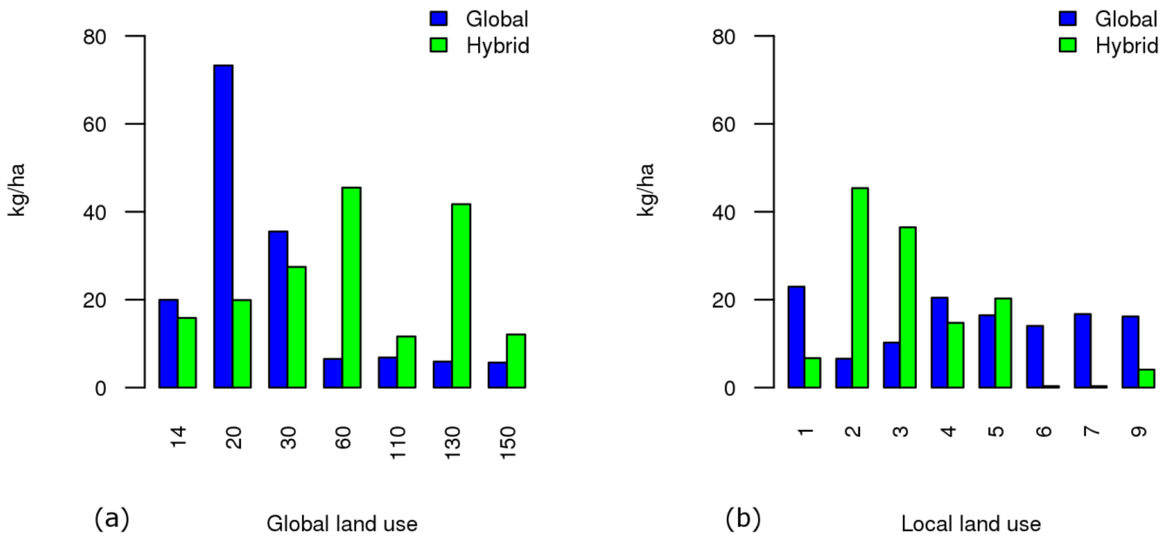

Figure 9. Histograms of median nitrogen retention (kg ha^{-1} yr^{-1}) per global (a) and local (b) land use classes. The results obtained in the global modelling are represented in blue, while the results obtained in the hybrid modelling are in green.

4.2.2. Nitrogen export modelling

Outputs of the nitrogen export modelling were i) the indication on how much load from each pixel eventually reaches the stream, and ii) the total amount of nitrogen exported to the stream per each sub-catchment.

The mean nitrogen export for the whole area in scenario A, B and C was 2.06, 2.85 and 3.66 kg ha^{-1} yr^{-1} in the global modelling and 2.19, 2.97 and 3.87 kg ha^{-1} yr^{-1} in the hybrid modelling.

The linear regression models between global and hybrid results showed good fitting at sub-catchment level with R^2 that ranged in the three scenarios from 0.72 and 0.82, while lower correlations were obtained at pixel level with R^2 that ranged in the three scenarios from 0.43 to 0.67 (see Fig. 2). Good correlation between global and hybrid modelling was found by the rank correlation analysis at both pixel and sub-catchment resolution. For the three scenarios the rank correlation coefficient was 0.91 at pixel resolution and ranged from 0.81 to 0.85 at sub-catchment resolution.

The three scenarios showed very similar spatial distribution. Therefore, only the results for scenario C (high N loading) are represented and further discussed.

Fig. 10 shows the nitrogen export spatial distribution for the scenario C in the global and the hybrid modelling. The maps showed that the nitrogen export estimates followed a hydrographic spatial distribution with higher values closed to possible water ways.

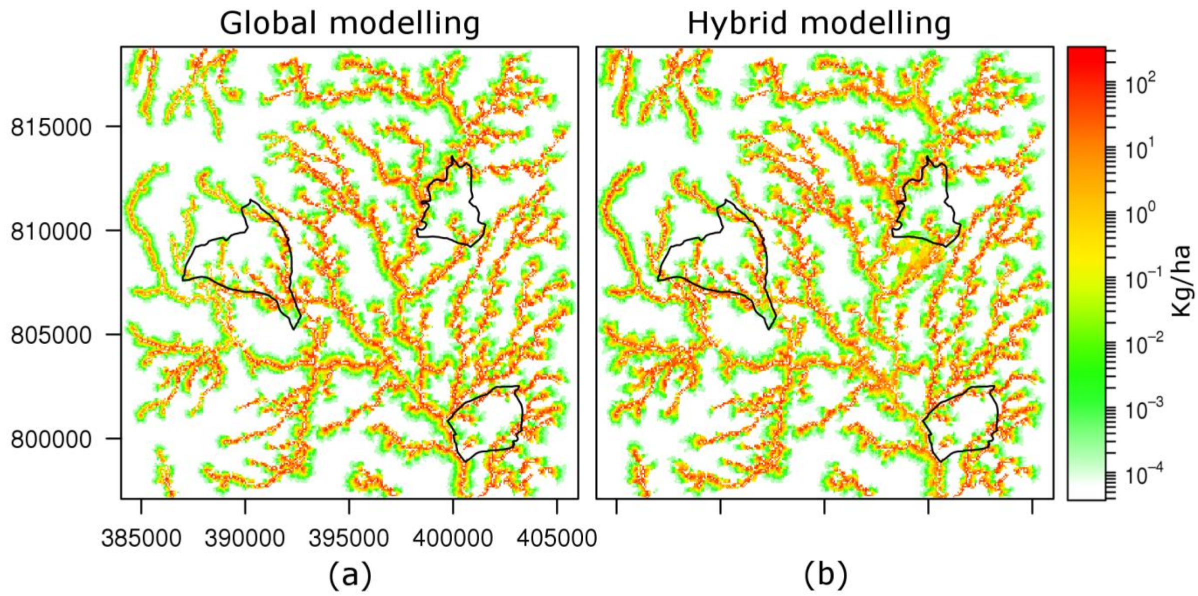

Figure 10. Spatial representation of the nitrogen export in the global (a) and in the hybrid (b) modelling.

Fig. 11 shows the spatial distribution of the nitrogen export at catchment resolution of the scenario C. The western catchments showed less nitrogen export (kg yr^{-1}) in the global modelling, higher values were estimated by the hybrid modelling. In the eastern area higher values of N export were instead obtained using the global dataset.

The histograms in Fig. 12 show the mean value of nitrogen export (kg ha^{-1} yr^{-1}) per global (12a) and per local (12b) land use classes in scenario C. In blue are shown the results obtained using the global dataset and in green are shown the results obtained using the hybrid dataset. The mean nitrogen export per global and local land use classes obtained in the global and in the hybrid modelling showed a different pattern. At local land use level (Fig. 12b) the higher nitrogen export was estimated by the hybrid modelling for the class 3 (settlement and farmland alongside settlements) followed by the classes 7 (riverine areas) and 4 (degraded land), whereas the global modelling estimated higher nitrogen in the local land use classes 7 and 9 (grassland areas). At global land use level (Fig. 12a) the higher nitrogen export was estimated for the class 20 (mosaic cropland) followed by classes 14 (rainfed cropland) and 30 (mosaic vegetation and cropland) in both the global and the hybrid modelling.

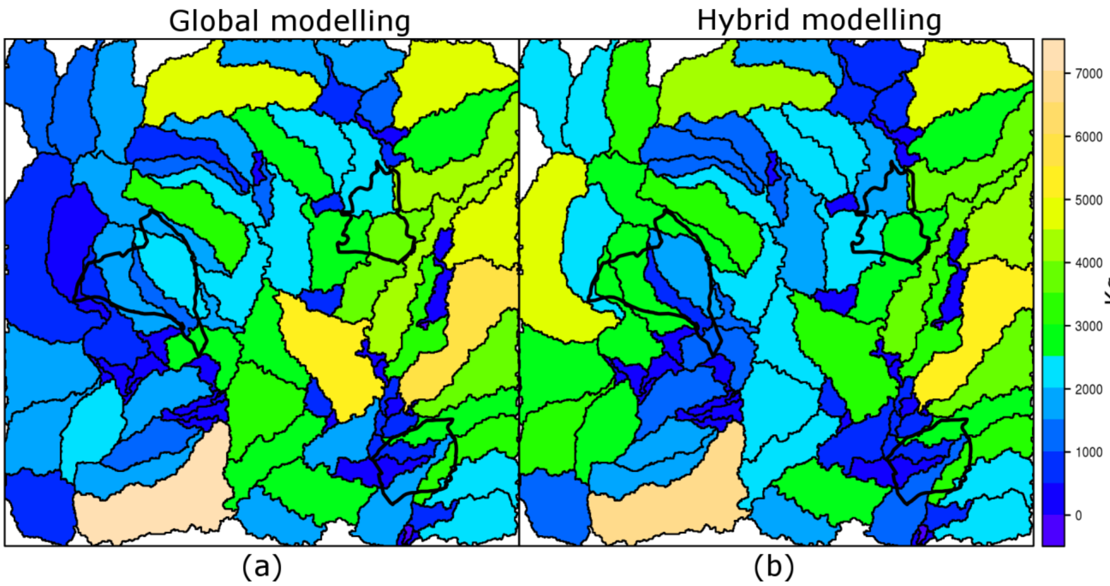

Figure 11. Sub-catchment spatial distribution of nitrogen export in the global (a) and the hybrid (b) modelling.

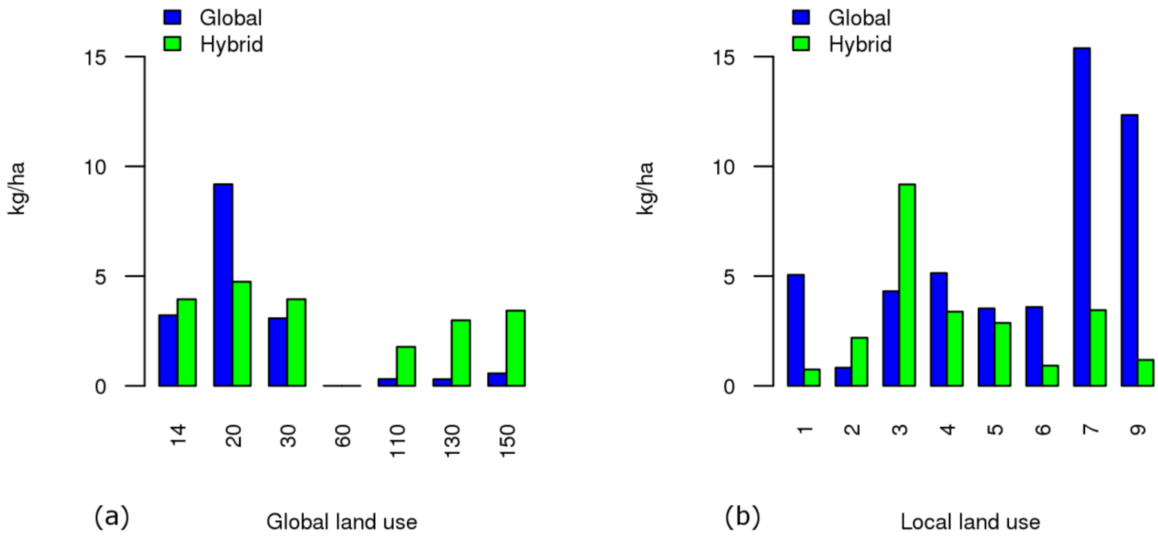

Figure 12. Histograms of mean nitrogen export (kg ha^{-1} yr^{-1}) per global (a) and local (b) land use classes. The results obtained in the global modelling are represented in blue, while the results obtained in the hybrid modelling are in green.

5. Discussion

5.1. ESS modelling and reliability of global data

The chosen ESS modelling approaches have some limitations that should be considered when assessing the results. The sediment erosion and retention modelling used the well-known USLE equation approach in the revised model (RUSLE). The USLE equation can mainly model sheet and rill erosion processes, whereas other sources of erosion are not well represented using the USLE (e.g. mass, streambank, and gully erosion). Gully erosion is important in the area and generally in the Ethiopian landscape (Nyssen et al. 2006; Nyssen et al. 2009b), therefore the results obtained could be an underestimation. Moreover, the USLE/RUSLE methods have limitations in their ability to take into account short-term variability of rainfall, therefore, ignoring the seasonal rainfall patterns.

The InVEST Nutrient Retention: Water Purification model is a simplified approach. The model assumes that there is continuity in the hydraulic flow path. Moreover, it does not address chemical or biological interactions that might occur from the loading point through the point of interest, besides filtration by terrestrial vegetation. Nitrogen might in fact degrade over time and distance through interactions with the air, water and/or bacteria (Sharp et al. 2015). However, these limitations and model simplifications do not affect the comparison analysis among the results derived from the two sets of data that has been studied here. InVEST tool was chosen, among other ESS modelling tools, such as ARIES - Artificial Intelligence for Ecosystem Services (Villa et al. 2009; Bagstad et al. 2011), because it develops simple ESS models that are widely used (Nelson et al. 2009; Nelson et al. 2010; Polasky et al. 2011; Kovacs et al. 2013; Leh et al. 2013; Bhagabati et al. 2014).

Other uncertainties in the hybrid modelling results could be derived from the upscaling of the soil properties data based on the samples.

Quality satellite images for recent years (Biazin and Sterk 2013) are often difficult to find due to cloud cover during the vegetative season, and in large areas of Ethiopia, remote sensing images with low or no cloud cover are exclusive of the dry season. This aspect made it often difficult to distinguish automatically between different land use classes (e.g. degraded lands, croplands and grasslands) without direct visual interpretation because of their similar spectral reflectance (Hurni et al. 2015).

The possible errors in using unsupervised classification on global satellite products for assessing land degradation were clear, especially when land use was used in the modelling. The nitrogen load was strongly dependent on land use classes. Due to the different characteristics and spatial distributions among global and local land use classes different estimates were found for both N retention and N export modelling.

These results highlighted the potential problems associated with ESS assessment that rely on land use. It has become widespread practice to use a look-up table approach to assess services and also upscale results over large areas. My results clearly demonstrated that results are sensitive to the land use map used and that substantial error could be introduced when using global land use/cover maps. This problem is likely to apply to any classification, so the importance of the accuracy and thematic resolution of the land cover map should not be underestimated in and ESS studies. When land use is used as an ESS indicator or to estimate ecosystem services, the accuracy at the needed regions or scale could be affected leading to unreliable results. In regional studies, it could be recommended the use of high resolution remote sensing data to derive a reliable land use data and/or amend existing global medium resolution products. However, this study concur with Eggen et al. (2016), Hurni et al. (2015) and Wondrade et al. (2014), who remarked that mapping land cover using remote sensing in Ethiopia is often a challenge not only because of the absence of suitable remote sensing images representative of the vegetative season but also due to the heterogeneity of the Ethiopian landscape originated by a long history of smallholder cultivation.

The coarse scale resolution of many global datasets that are often used to parametrise ESS models (Andrew et al. 2015) is also a problem if the ESS assessment aims to support decision-making and planning processes. For example, to accommodate the resolution of the inputs data, the soil erosion and retention returned results at 250 m resolution if the global dataset was used, or at 30 m resolution if the local dataset was used. Results of 250 m resolution are less reliable and not detailed enough if areas for intervention need to be identified.

Furthermore, the use of coarse global climatic data due to of the absence of locally detailed and reliable data could also have affected my results, obtained using both the global and the hybrid datasets.

Throughout ESS assessment, important areas could be identified as priority areas for restoration and conservation purposes. However, ESS assessments obtained using global datasets could introduce inaccuracy and limitations that constrains their adoption as decision-making tools. Detailed datasets are crucial in estimating variation at local level that could be relevant at decision-making perspective (Vihervaara et al. 2012). For example, in this study the global land use classification affected nitrogen retention and export modelling leading to unreliable results. The global land use led to opposite nitrogen retention and export modelling results compared to hybrid modelling results. The global land use led to opposite nitrogen retention and export modelling results compared to hybrid modelling results, especially in certain areas, because of different nitrogen loading spatial patterns. Therefore, in the western hilly area, the hybrid modelling found higher retention as well as higher export compared to the global modelling due to completely different loading patterns derived by different land use classification. These could lead to wrong interpretation at decision-making level, e.g. by leading to suggest and support an increase in loading instead of supporting better soil and water conservation structures implementation in order to take advantage of the high potential nitrogen retention of the area. In this context, good knowledge of the area and a good land use classification turned out to be crucial to individuate proper restoration and management strategies based on ESS assessment. Pandeya et al. (2016) stressed that often the lack of locally relevant data is the main constraints for the integration of ESS frameworks in decision-making processes. Nevertheless, considering both the soil and the nitrogen modelling, it is possible to infer that general planning strategies could be taken even using ESS assessments derived using global datasets. In this study, for example, also because of the absence of local reliable climatic data, the soil erosion and retention global and hybrid modelling results showed good correlation. Therefore, global datasets proved to be suitable especially in the erosion modelling. For example, the spatial distribution of soil erosion was similar in the global and in the hybrid modelling results. Although the range of values differed between the two modelling types, the spatial distribution was not affected. In this respect, a study on digital soil mapping by Cavazzi et al. (2013) found that fine resolution mapping not always constitutes the best approach for modelling, indicating that in flat homogeneous areas coarse resolution mapping produced better performances than a finer resolution mapping. However, spatially explicit models can be obtained just using local data and detailed land use classification. This is the case of the nitrogen retention and export modelling where different land use classifications (global or local) led to very different results affecting possible future decision-making strategies. These results concurred with Grêt-Regamey et al. (2014) who found that ESS estimates differed between fine and coarse resolution modelling especially in less rugged terrain, and identified the land use data as an important variable in affecting the ESS estimates. Therefore, to implement more detailed and focused decision-making strategies, data spatial details and accuracy are needed especially when priority conservation interventions and areas need to be identified through ecosystem services modelling and mapping.

5.2. Soil erosion and retention modelling

5.2.1. Soil erosion modelling

The good correlation between global and hybrid soil erosion and retention modelling results (Fig. 2) was not surprising and was mainly due to the fact that the global and the hybrid modelling shared the same datasets apart from the K factor and the P factor (see Table 1).

Despite the overall soil erosion reduction due to the P factor, higher soil erosion rate was estimated by the hybrid modelling. This was because of the higher K factor in the hybrid dataset. K factor ranged from 0.022 to 0.029 with a mean of 0.026 and from 2e-5 to 0.055 with a mean of 0.039 in the global dataset and in the hybrid dataset, respectively.

The spatial distribution of soil erosion at sub-catchment level (Fig. 4) showed higher total erosion (t yr^{-1}), in both the global and the hybrid modelling, in the western area characterised by slope and steep areas. Layignaw Arsho *kebele* proved to be the most affected by soil erosion due to its location at the feet of higher elevations where the slope increases.

My results appeared generally realistic if compared to soil erosion rates estimated by previous studies in Ethiopia both at national and local spatial resolution. Bewket and Teferi (2009) estimated annual soil erosion from 0 to 125 t ha^{-1} yr^{-1}. Ali and Hagos (2016) estimated in the Hawassa sub-catchment, about 50 km south east of my study area, a soil erosion rate of 0-5 and 5-202 t ha^{-1} yr^{-1} in approximately 95%, and 5% of the whole area, respectively. Herweg and Ludi (1999) estimated a soil erosion range of 0-167 t ha^{-1} yr^{-1} in seven research sites in Ethiopian and Eritrean highlands, with a considerable soil loss reduction under SWC measures implementation. Despite the crucial role of SWC measures in reducing soil erosion, in one site an annual soil erosion rate of more than 30 t ha^{-1} yr^{-1} was recorded (Herweg and Ludi 1999). My results are consistent also with the average soil loss of 35 t ha^{-1} yr^{-1} of the Ethiopian Highlands that increased to 130 t ha^{-1} yr^{-1} if just cropland are considered (FAO 1986).

The high variability in estimates of soil erosion rates in my study and in previous Ethiopian studies is probably caused by the high diversity in climate patterns, geomorphology, traditional farming activities and management as well as in soil type and vegetation cover that characterised Ethiopia (FAO 1986; Herweg and Ludi 1999).

5.2.2. Soil retention modelling

Despite variable spatial patterns, higher soil retention rates were estimated, by both global and local modelling, in the western part of the study area, mainly characterised by higher altitude and vegetation cover derived from agroforestry practices (see Fig. 6).

Median soil retention of 3.6 and 5 t ha^{-1} yr^{-1} was estimated in the global and the hybrid modelling, respectively. As for the soil erosion, also the soil retention modelling estimated higher rates using the hybrid dataset. This was mainly due to the P factor that led to an increase in retention capacity in certain areas using the hybrid modelling. The higher soil retention rates were estimated in the areas where the C factor (in the global modelling), and the P factor together with the C factor (in the hybrid modelling) reduced the potential soil erosion. Higher soil erosion potential of western areas led also to higher soil retention (or avoided soil erosion) estimates because if the area has high potential erosion rate more soil can potentially be retained by the ecosystem if there is high vegetation cover (C factor) as well as if conservation measures are implemented (P factor).

Unlike the soil erosion estimates, no previous Ethiopian studies exist to compare my results. Studies estimated the sediments retained or trapped by dams (Mekonnen et al. 2015) or reservoir (Haregeweyn et al. 2012). Moreover, other studies (Herweg and Ludi 1999; Gebremichael et al. 2005; Taye et al. 2013) estimated the reduction on soil erosion after the implementation of SWC measures, estimating the soil trapped and retained by the soil and water conservation (SWC) structures. For example, Gebremichael et al. (2005) found average sediment accumulation of 59 t ha^{-1} yr^{-1} behind stone bunds in Tigray Ethiopian region. This result is similar to my results that estimated mean sediment retention of 44 and of 54 t ha^{-1} yr^{-1} in the global and the hybrid modelling, respectively, for the whole area. Another study (Taye et al., 2013) found a soil loss reduction of 63% and 47% in rangeland and cropland, respectively, after the implementation of stone bunds. My study estimated a median soil erosion reduction or sediment retention of ~60% in both global and hybrid modelling. However, my results estimated the soil retained due to vegetation cover (C factor) or conservation structures (P factor), whereas the aforementioned studies considered just the role of SWC structures in reducing soil erosion through trapping and accumulating sediments beyond the conservation structures.

5.3. Nutrient modelling

5.3.1. Nitrogen retention modelling

Unsurprisingly, the mean nitrogen retention (kg ha^{-1} yr^{-1}) gradually increased from scenario A (low loading) to scenario C (high loading) in both global and hybrid modelling.

Higher nitrogen retention estimates were obtained using the hybrid dataset mainly because of the different loadings spatial patterns derived by using different land use classifications, as well as because in the global land use the extension of natural and semi-natural classes, which received just nitrogen from atmospheric deposition (7.5 kg ha^{-1} yr^{-1}), were larger. This led to a lower nitrogen loading in the global modelling (N loading average in the three scenarios: ~32-57 kg ha^{-1} yr^{-1}). In the local land use the semi-natural areas were instead smaller therefore much nitrogen was loaded in the ecosystem (N loading average in the three scenarios: ~35-63 kg ha^{-1} yr^{-1}).

At land use classes level, the results of the global and hybrid modelling differed with different ranges in all the global, as well as local land use classes (Fig. 9). The spatial differences were mainly due to the different loadings and vegetation filtering efficiency spatial patterns derived by using different land use covers. The importance of detailed land use cover for modelling the nutrient retention was highlighted by Redhead et al. (2018) that found high impacts on model performance using land cover map with resolution coarser than 100 m. In my study, the global land cover, apart from coarse resolution (300 m), showed also unreliable spatial distribution failing to realistically characterise the landscape. For example, the hilly area in the western part of the area received much lower loading in the global modelling because the class that occupied that area was described as “closed to open (15%) shrubland (<5m)” (class number 130), whereas in the local land use the same area was mainly occupied by the class 2 (forests and farmland in hilly area). This aspect led to a difference of approximately 40 kg ha^{-1} yr^{-1} in the median nitrogen retention per sub-catchment. Sub-catchments that present higher values in the global modelling were instead mainly located closed to Halaba town and Andegna Choroko *kebele*. The town areas presented lower vegetation filtering efficiency as well as lower loading in the hybrid modelling, while in the global modelling these aspects were not considered since the global land use cover didn’t present any settlement or urban categories.

5.3.2. Nitrogen export modelling

The nitrogen export followed a topographic and hydrographic distribution that it is clearly highlighted by the spatial representation in Fig. 10.

Higher loadings in the western part of the study area in the hybrid datasets led to higher nitrogen export estimates in the hybrid modelling, whereas an opposite pattern characterised the eastern part of the areas. See through land use based summaries, the two modelling results showed very different mean nitrogen export patterns (Fig. 12). Like the nutrient retention modelling, these differences were mainly caused by the different spatial patterns of the loadings among global and hybrid datasets.

Despite variable spatial patterns, both the global and the hybrid modelling estimated an average retention of about 93% of the loading and an average export of about 6% in all the three scenarios showing a good correlation between the two modelling at a broader scale. This was determined by the fact that the two datasets shared the same spatial data apart from the plant available water map, while the main differences were introduced by using different land use classifications.

The mean nitrogen export estimates in both the global (2.06-3.66 kg ha^{-1} yr^{-1}) and the hybrid (2.19-3.87 kg ha^{-1} yr^{-1}) modelling were lower compared with the N export of different African river reported by Caraco and Cole (1999) who noted a range of 3-30 Kg ha^{-1} yr^{-1}. For Nile and Orange rivers, nitrogen exports of 3 and 4 kg ha^{-1} yr^{-1} are reported. Higher values are reported for the rivers Zaire, Niger and Zambezi with export of 30, 21 and 10 kg N ha^{-1} yr^{-1}, respectively. Girmay et al. (2009) found a sediment-bound nitrogen export of 2.1-32.8 kg ha^{-1} yr^{-1} with lowest value in the exclosures and highest in cultivated land.

If this type of assessment aims to be used at decision-making level the land use map needs to be reliable, otherwise wrong interpretation could lead to implementation of wrong strategies at local or even national level.

5.4. Land and ecosystem services degradation

The high potential in nitrogen retention, estimated in both the global and the hybrid modelling, suggested that an increase of inorganic and organic fertilisers application would be highly recommended in the Halaba *woreda*, where farmers struggle to achieve proper yields for their household subsistence (Getnet et al. 2017). However, the application of the recommended rate of inorganic fertiliser is limited by capacity constraints, and the utilisation of manure is limited by the shrinking number of cattle per household, by the transport constraints and by the habit of using it as fuel (FAO 1986; Desta et al. 2000; Gebreselassie 2006). Usually in Ethiopia farmyard manure application is therefore limited to the homestead farm (Haregeweyn et al. 2008; Girmay et al. 2008). Moreover, application of fertilisers is effective just in combination with implementation of SWC measures that provide a better water retention (Hurni et al. 2015), and that reduce soil erosion, one of the key causes of soil nutrient depletion (Haileslassie et al. 2005; Haregeweyn et al. 2008). Haregeweyn et al. (2008) estimated that soil erosion accounts for loss of 70%, 80% and 63% of total nitrogen stock, available phosphorus and total potassium stock, respectively, leading to soil fertility depletion. From this study results, it can be argued that fertiliser application should be recommended just in conjunction with better and sustainable land management, and restoration activities, which aim to reduce soil erosion and to increase soil quality and water retention. Inorganic fertilisers alone would probably increase the risk of promoting land degradation risk, exacerbating the already serious situation.

Extensive implementation of SWC measures becomes vital considering the high potential soil erosion rate estimated. Soil and water conservation structures have a key role in preserving the fragile soil of the Ethiopian highlands, by reducing soil erosion and land degradation (Grunder 1988; Herweg and Ludi 1999; Gebremichael et al. 2005; Descheemaeker et al. 2006), and increasing soil fertility and thus enhancing crops production (Vancampenhout et al. 2006; Hailu 2017).

Conservation on Ethiopian farmland was implemented on a broader scale with the introduction of conservation and restoration programs after the great famine that seriously harmed Ethiopia in 1972-1973 (Hurni et al. 2010). Also in the Halaba *woreda* efforts have been made to reduce land degradation and improve livelihood resilience (Getnet et al. 2017; Byg et al. 2017). Despite the serious land degradation that affects Ethiopian landscape, Nyssen et al. (2009) proved that reversing land degradation trends is possible, if proper efforts are made into restoration and conservation activities. However, Hurni (1993) emphasised that there are multiple factors to account for; a stable scenario that aims to a long-term sustainable use of the land resources at country scale can be achieved only if conservation and restoration efforts are accompanied by family planning programs. Moreover, a study about exclosures services and disservices in the same study area of this study (Byg et al. 2017) emphasised that participation of local communities should be guaranteed in order to better identify and recognise possible trade-offs and disservices of designed restoration activities and interventions. This is key for contributing not only to ecosystem restoration, but also to human well-being and poverty eradication (Byg et al. 2017). Therefore, to reduce land and ecosystem services degradation, it is crucial to integrate socio-political and economic aspects together with land management and conservation approach.

6. Conclusions

Ecosystem services mapping represents an effective means to evaluate land degradation. The approach presented in this study contributes to identifying priority areas, as well as priority interventions in order to reduce land degradation, and promote sustainable use of the soil. While the global data sets examined in this study have a clear role in establishing national or continental scale strategic priorities and trends, the study results showed that care must be taken when using them in applications at the small sub-catchment or small region scale, especially if land use classification is an important variable in the estimation of ecosystem services.

This study recommends, whenever feasible, the integration of unsupervised and supervised classification of high resolution satellite data, and their integration with local data sets, based on field activities, to achieve a reliable assessment.

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CHAPTER 3

The implications of modelling carbon storage and sequestration to infer land degradation using globally available data and different scales[2]

[2] This Chapter was modified from the manuscript "The implications of modelling carbon storage and sequestration to infer land degradation using globally available data and different scales. An Ethiopian case study" submitted at the Science of the Total Environment Journal (under review).

Authors: Stefania Cerretelli[*,a,b,c], Laura Poggio[a], Alessandro Gimona[a], Getahun Yakob[d], Shiferaw Boke[d], Mulugeta Habte[d], Malcolm Coull[a], Alessandro Peressotti[b], Helaina Black[a]

* Corresponding author, [a] The James Hutton Institute (United Kingdom), [b] University of Udine (Italy), [c] University of Trieste (Italy), [d] Southern Agricultural Research Institute (Ethiopia)

1. INTRODUCTION

The majority of factors linked to land degradation (e.g. soil erosion, overgrazing, deforestation, mismanagement) are crucial factors also in affecting carbon storage and sequestration, and in depleting organic carbon stocks. Carbon sequestration has a crucial role in climate regulation by reducing carbon emission (CO_2 emission). Hence, restoring degraded agroecosystems is considered a viable strategy in order to reduce carbon emissions, by enhancing carbon sequestration and increasing soil carbon benefits (Lal 2006). Carbon storage and sequestration is important for CO_2 and climate regulation and mitigation, as well as for soil quality and crop yields (Jobbágy and Jackson 2000; Rawls et al. 2003; Lal 2004a; Lal 2004b; Lal 2006; Minasny et al. 2017). In particular, soil organic carbon (SOC) stock is strongly linked to soil quality (Lal 2006).

Concerning SOC, an important mechanism linked to carbon sequestration to tackle and compensate global greenhouse gases emission is the “4 per mille Soil for Food Security and Climate”. The program was developed under the Lima-Paris Action Agenda (LPAA), and was launched during the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21) hold in Paris (November 30-December 1, 2015). This initiative aims to increase global soil organic carbon (SOC) stock by 0.4 percent per year in order to compensate greenhouse gases emissions by anthropogenic sources (Minasny et al. 2017). The “4 per mille” proposal promotes SOC sequestration mainly by encouraging sustainable management practices in agricultural lands (Lal 2016) that, on the other hand, will promote food security by improving soil structure and retention, nutrient cycling and soil fertility (Lal 2004a; Lal 2006).

In Ethiopia, carbon sequestration have been studied to highlight the crucial role of forests in climate change mitigation (Moges et al. 2010; Alemu 2014). Other studies focused their attention on the role of land management in affecting soil organic carbon and soil fertility (Lemenih et al. 2004; Yimer et al. 2007; Girmay et al. 2008) and on the role of forest composition and management in carbon sequestration (Solomon et al. 2017). Carbon sequestration gained high attention in Ethiopia from the 2006 when the country started adopting the REDD+ (Reducing Emissions from Deforestation and forest Degradation, “plus” afforestation) mechanism (Gonzalo et al. 2017), a tool that supports and incentivises forest carbon-enhancing approaches in order to reduce deforestation rates and greenhouse gases emissions. Nonetheless, in Ethiopia not many studies assessed the total carbon storage (Vanderhaegen et al. 2015; Bajigo et al. 2015; De Beenhouwer et al. 2016). More studies attempted to quantify and estimate the carbon stored in the aboveground biomass in different areas of Ethiopia, especially in forests, plantations or agroforestry systems (Moges et al. 2010; Amsalu and Mengaw 2014; Tadesse et al. 2014; Wondrade et al. 2015; Denu et al. 2016; Solomon et al. 2017). Furthermore, in Ethiopia several studies assessed the soil organic carbon stock. Soil organic carbon stock and more in general soil organic matter (SOM) have a key role in soil fertility, soil functions, nutrient cycling and water retention (Lal 2015). Soil organic carbon stocks depend on several factors such as climatic factors (e.g. temperature, precipitations), management aspects (e.g. crop residues retention, fallow implementation, tillage type, manure inputs), soil type and texture, and land cover aspects (vegetation type and agricultural activities) (Jobbágy and Jackson 2000; Fantappiè et al. 2010; Stockmann et al. 2015; Minasny et al. 2017).

Studies of Ethiopian ecosystems have shown that soil organic carbon (SOC) stock and soil organic matter (SOM) content strongly depend on land use and vegetation types (Bewket and Stroosnijder 2003; Lemenih and Itanna 2004; Lemenih et al. 2004; Girmay et al. 2008), as well as on land agricultural management (Rimhanen et al. 2016) and grazing intensity (Bewket and Stroosnijder 2003). Land use changes, as well as soil erosion, and removal of crop residues from cropland are reported as the major drivers of SOC loss by Girmay et al. (2008).

In order to select and adopt certain restoration activities and identify priority areas for interventions, decision-making processes rely on the modelling of spatial targets. In this context, above and below ground carbon stock represents a good indicator of land degradation (UNCCD et al. 2016). More in details, SOC represents an important indicator of land and soil degradation, because it affects several key soil functions (Baldock et al. 2009; Vågen et al. 2012; Vågen et al. 2013; Stockmann et al. 2015; Lal 2015).

Therefore, modelling and mapping carbon storage and sequestration can facilitate and support precise and accurate interventions and actions. However, the assessment needs to be accurate in order to be considered at a decision-making level (Vihervaara et al. 2012; Pandeya et al. 2016).

However, local detailed data limitation represents often an important limiting factor in mapping ecosystem services over large areas especially in Africa (Liu et al. 2008). Lack of quality satellite images for recent years and with low cloud cover and absence of up-to-date land cover dataset are also indicated as important limiting factors in assessing ecosystem services benefits in Ethiopia (Biazin and Sterk 2013; Hurni et al. 2015; Eggen et al. 2016). Therefore, in data-poor area often decision-making rely on data from global coverage datasets.

The study area, located in the Ethiopia Great Rift Valley, is highly harmed by land degradation. In the last decades, several restoration projects have been adopted in order to reduce land degradation and soil erosion. Therefore, mapping and assessing carbon storage and sequestration in the study area appears to be crucial in order to target priority areas for restoration, and identify feasible measures to increase carbon stocks aiming to reduce land degradation. This study tried to address if global data are good enough for this purpose.

Overall, this study aimed to assess carbon storage and sequestration to infer land degradation risk, and assess possible implications and limitations of mapping carbon storage and sequestration using global coverage data at a small and local scale. The importance of scale dependency in modelling environmental aspects have been highlighted by previous studies that found how data resolution and extent could affect digital soil mapping, ESS modelling, and species richness and distribution mapping (Sobieraj et al. 2004; Foddy 2004; Rahbek 2005; Cavazzi et al. 2013). Grêt-Regamey et al. (2014) assessed the effect of scale on ESS mapping and found substantial differences between the fine and coarse resolution analyses especially when local heterogeneity was an important factor. This study aimed to identify the difference on carbon storage and sequestration modelling results obtained using different sets of data, which differed in resolution and extent. The main objectives of this study were to:

- compare the results obtained using different datasets, one that integrates global data with local survey data and supervised land use classification, and one that is composed by data from global datasets exclusively;
- evaluate the extent of land degradation using as indicator the carbon storage and sequestration amount that is mapped using GIS and Remote Sensing approach;
- assess and identify possible advantages, disadvantages and limitations in mapping carbon storage and sequestration using different scales of resolution.

2. DATASETS

2.1. Data sources

In this study, two different datasets, characterised by different soil organic carbon (SOC) and land use cover data sources, were used (see Table 1). A "global dataset" included data just from readily available data with global coverage (see Appendix A, Section 2.2.1 and Section 2.2.2), and a "hybrid dataset" integrated global data with SOC derived from interpolation of data from local survey carried out during 2015, and a supervised land use classification data. Remote sensing dataset were derived from Landsat, MODIS (Moderate Resolution Imaging Spectroradiometer), Sentinel 1 and Sentinel 2 sensors. SRTM (Shuttle Radar Topography Mission) dataset was used for morphological information (e.g. elevation, slope). Global soil organic carbon (SOC) stock data, used in the global modelling, were downloaded from the ISRIC International Soil Reference and Information Centre) database (*ftp://ftp.soilgrids.org/data/recent/*) (Hengl et al. 2017). For further details on the global datasets used see Appendix A, Section 1.

Table 1. Description of global and hybrid datasets. In brackets are reported the units of the input variables and their resolution in global and hybrid datasets. NDVI: Normalised Difference Vegetation Index; NPP: Net Primary Productivity; GLNC: Global Land Cover Network.

	Input variables	**Global dataset**	**Hybrid dataset**
Carbon modelling	SOC (t ha^{-1})	- ISRIC (250 m)	- Local samples; bulk density and organic matter content (25 m)
	Carbon from above- and below- ground biomass (t ha^{-1})	- Landsat NDVI (30 m) - Land cover from GLNC (300 m)	- Landsat NDVI (30 m) - Land cover from supervised classification (30 m)
	Carbon from dead organic matter (t ha^{-1})	- MODIS; NPP (~1 km)	- MODIS; NPP (~1 km)

2.1.1. Land use from global database

The FAO Land Cover of Ethiopia map was derived from the Global Land Cover Network (GLNC), a global cover archive of 300 m spatial resolution (Arino et al. 2008; FAO 2009; Arino et al. 2010). The GlobCover has been reprocessed to generate database at national extent, with few adaptations to the legend. For this study, the Ethiopian version downloaded from the FAO GeoNetwork database (*http://www.fao.org/geonetwork /srv/en/main.home*) was used. Fig. 1 shows the land use of the study area according to the global data and classification, while Table 2 shows the global land use classes' description and an approximate correspondence with the local land cover classes (see for comparison Table 5).

Table 2. "Global" land use classes description. See Table 5 for corresponding local land use classes' description.

Global LU Class	Corresponding local LU class	Description	Percentage of study area (%)
14	5	rainfed cropland	54.6
20	3	mosaic cropland (50-70%)/vegetation (grassland/shrubland/forest) (20-50%)	17.1
30	2	mosaic vegetation (grassland/shrubland/forest) (50-70%)/ cropland (20-50%)	7.7
60	1	open (15-40%) broadleaved deciduous forest/woodland (>5m)	0.1
110	NA	mosaic forest or shrubland (50-70%)/grassland (20-50%)	0.9
130	NA	closed to open (15%) shrubland (<5m)	19.6
150	NA	sparse (<15%) vegetation-sparse woody vegetation/herbaceous sparse vegetation.	0.2

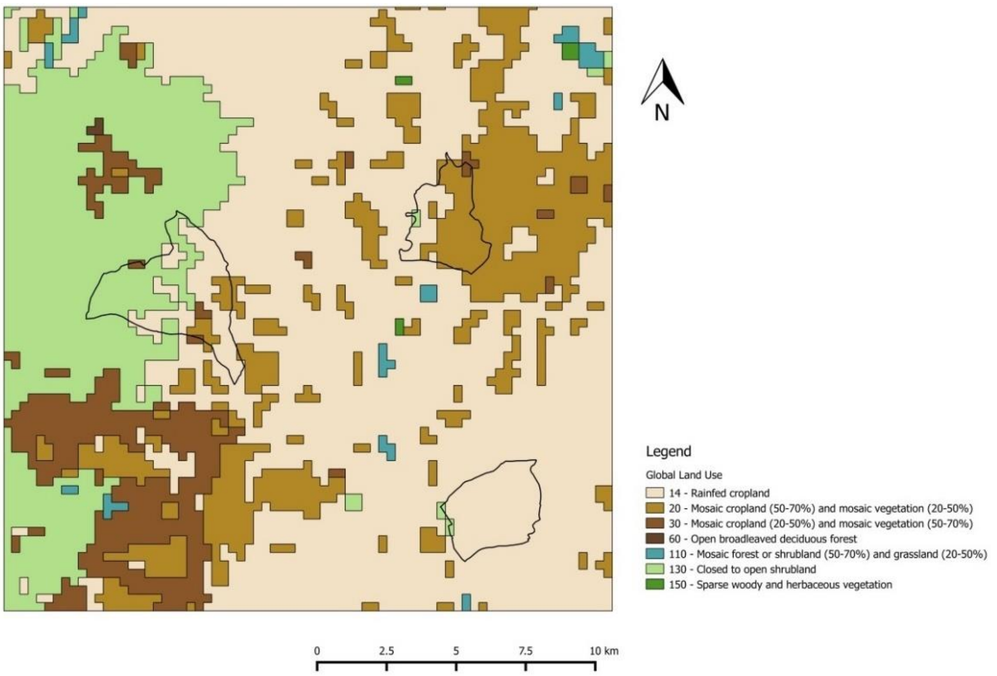

Figure 1. Global land use.

2.1.2. Global soil data

Global SOC stock data, used in the global modelling, were downloaded from the ISRIC (International Soil Reference and Information Centre) – World Soil Information, SoilGrids 250m dataset (*ftp://ftp.soilgrids.org/data/recent/*), a global collection of soil properties maps at 250 m spatial resolution. It was produced using automated soil mapping based on machine learning algorithms (Hengl et al. 2017). In particular, the soil organic carbon stock (t ha^{-1}) was derived based on the predictions of soil organic carbon content (‰), bulk density and coarse fragments volume (Hengl et al. 2014).

2.2. Local soil and land use survey

Soil local data were derived from samples collected during a local survey carried out in the 2015 (Black et al. 2015). Totally 354 samples were collected for 20 cm of soil depth from: i) different fields of 75 selected households in the three *kebeles*; ii) 108 semi-natural sites and farmland sites, and iii) 6 restoration sites of different ages (see further details in Appendix A, Section 2).

In this study, the SOC amount was derived from data on soil organic matter percentage and bulk density of the 354 samples collected for 20 cm of soil depth (see Section 3.4).

3. METHODS

The procedure used to model carbon storage and sequestration and to analyse the obtained results is highlighted in Fig. 2, in which three main steps are indicated: i) data collection to derive the "global" and the "hybrid" datasets; ii) carbon and sequestration modelling by calculating the three carbon pools (carbon from total living biomass, carbon from dead organic matter, and soil organic carbon; see Section 3.4); iii) statistical analysis for comparing the two sets of results (global and hybrid).

3.1. Land use classification

The local land use dataset used in hybrid dataset was derived using a two-step supervised classification. In the first step, 670 points were selected and classified using local expertise with the support of Google Earth® images. The 670 points represented different land use categories such as degraded land, woodland, riverine areas, cropland, rangeland, forest, settlement area. A first approximation of the local land use classification was obtained using a classification and regression trees approach (namely RandomForest; Breiman 2001) with the points and a number of covariates, derived from elevation, Landsat datasets, and Sentinel 2 scenes (see Section 2 of Appendix A for further details).

The derived land use classification was subsequently verified and manually modified using Google Earth® images as background. Several classified polygons categories were changed based on local knowledge of the area, in order to differentiate between land use classes that in the automated classification were confused (e.g. degraded land, restoration land and croplands) due to their similar reflectance spectrum. Furthermore, polygons derived from the classification and characterised by mixed semi-natural vegetation and agroforestry were differentiated from the forested areas. Areas characterised by small settlements and cropland alongside them were also individuated and differentiated from Halaba urban area or farmland areas. See Table 5 for details on local land use classes and Table 2 for comparison with the global land use.

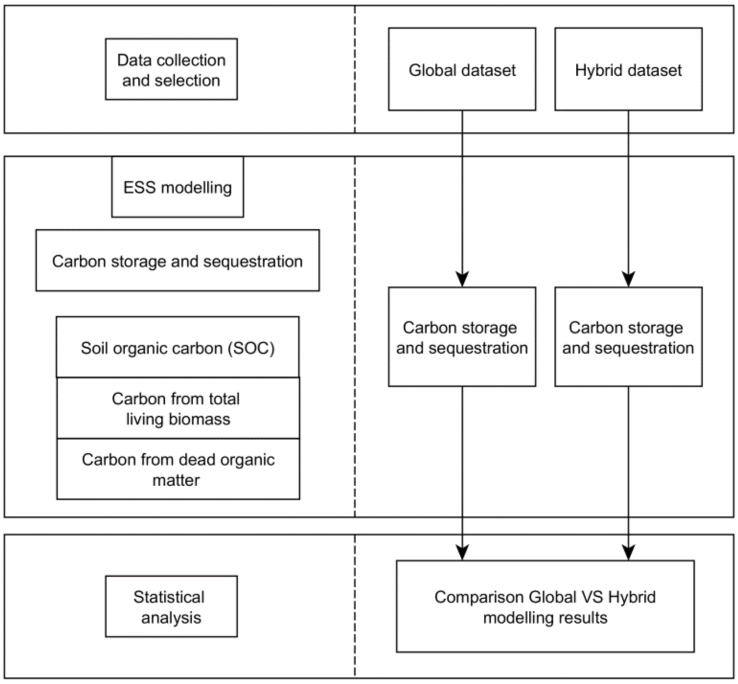

Figure 2. Flowchart. The left side shows the main general steps of the methods used in this study (data collection, carbon modelling, and statistical analysis). The right side shows the separate steps for both the two datasets (global and hybrid) used.

3.2. Global soil organic carbon data

Soil organic carbon stock data downloaded from the ISRIC SoilGrid 250m database (see Section 2.1.2) are expressed in t ha^{-1} for six depth layers (0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm, 100-200 cm) (Hengl et al. 2014; Hengl et al. 2017). The soil organic carbon stock for 20 cm depth was derived by summing the stock of the two first ISRIC layers of 0-5 cm and 5-15 cm, and just the stock of the first 5 cm (one third of the total depth interval) of the third layer (15-30 cm) assuming a constant soil organic carbon stock throughout the layer. Accordingly, the total amount for the 0-20 cm depth interval was obtained as follow:

$$SOC_{stock} = SOC_{d1} + SOC_{d2} + \frac{1}{3} SOC_{d3} \quad (1)$$

where:

SOC_{stock} = soil organic carbon (t ha^{-1})

$SOC_{d1\text{-}d3}$ = soil organic carbon at 0-5 cm (SOC_{d1}), 5-15 cm (SOC_{d2}), and 15-30 cm (SOC_{d3}) depth interval.

3.3. Local soil properties maps

Local soil properties maps, in particular soil organic matter (SOM) percentage and bulk density, were obtained through an interpolation process using an extension of the scorpan-kriging approach (McBratney et al. 2003). More in detail, a hybrid geostatistical Generalized Additive Models (GAM; Wood 2006), combining GAM with kriging (Poggio and Gimona 2014; Poggio and Gimona 2017) was used. A prediction grid of 25 m x 25 m resolution for the first 20 cm of soil depth was obtained (see Appendix A for further details).

3.4 Carbon storage and sequestration modelling

Three different carbon pools were considered:

i) soil organic carbon;

ii) carbon from total living biomass (aboveground and belowground biomass);

iii) carbon from dead organic matter. The amount of carbon from dead organic matter was derived from the NPP (Net Primary Productivity), assuming that the system was in equilibrium.

3.4.1. Soil organic carbon

Soil organic carbon for the hybrid modelling was calculated using the following equations (Van Bemmelen 1890):

$$SOC_{\%} = OM \times 58\% \quad (2)$$

$$SOC = SOC_{\%} \times BD \times (1 - VS_{\%}) \times SDT \quad (3)$$

where:

$SOC_{\%}$ = soil carbon content (%)

OM = organic matter content (%)

SOC = amount of soil organic carbon for a certain depth (t ha^{-1})

BD = bulk density (g cm^{-3})

VS = volume of stones (%)

SDT = soil depth thickness (cm)

For the global modelling, the map derived from the ISRIC SoilGrid 250m dataset, and calculated as in Section 3.2 was used.

3.4.2. Carbon from total living biomass

Equations that estimated plant biomass from NDVI index were used for characterising the biomass of different vegetation types; grassland: Devineau et al. (1986), forest: Gizachew et al. (2016), shrubland: Pereira et al. (1995), and cropland: Thenkabail et al. (2002). Table 3 summarises the equations used.

Table 3. Equations used to calculate the biomass. AGB = Dry aboveground biomass (t ha^{-1}). TLB = Total living biomass (above and below ground biomass) (t ha^{-1}). wAGB = wet aboveground biomass (t ha^{-1}). BGB = Belowground biomass (t ha^{-1}) calculated as in Kuyah et al. (2012).

	wAGB (t ha^{-1})	AGB (t ha^{-1})	BGB (t ha^{-1})	TLB (t ha^{-1})
Forest	-	-	-	$280.93 \times NDVI - 84.22$ (Gizachew et al. 2016)
Grassland	-	$\frac{(0.216 \times (100NDVI)^{1.7})}{100}$ (Devineau et al. 1986)	$0.49 \times AGB^{0.923}$ (Kuyah et al. 2012)	$AGB + BGB$
Shrubland	-	$2.923 + 21.486 \times NDVI$ (Pereira et al. 1995)	$0.49 \times AGB^{0.923}$	$AGB + BGB$
Cropland	$(0.186e^{3.6899 \times NDVI}) \times 10$ (Thenkabail et al. 2002)	$wAGB \times 0.905$	$0.49 \times AGB^{0.923}$	$AGB + BGB$

To obtain the dry cropland biomass, the moisture content (9.5%) was removed. The moisture content was obtained through a literature review on moisture content in cropland residues (McKendry 2002; Mani et al. 2004; Frear et al. 2005; Lam et al. 2007; Ben-Iwo et al. 2016; Guo et al. 2016).

The obtained total living biomass (t ha^{-1}) for the four different land covers were applied in different proportion for each global and local land use classes (see Table 4). This was necessary because the local land use classes, but also some of the global land use classes, represent a mosaic of different land use categories, due to the high heterogeneity of the Ethiopian landscape, and to the difficulties of distinguishing between different categories such as cropland and degraded land, forest and cropland around settlements.

Table 4 illustrates different proportions of total living biomass obtained through the four regression equations reported above applied in each land use class (e.g. for area occupied by the global land use class 60 and the hybrid land use class 1 that represent forest classes, I derived the biomass by adding at the biomass obtained using the equation for forest environment (Gizachew et al. 2016) 30% of the biomass obtained using the equation for grassland environment (Devineau et al. 1986), assuming the presence of biomass from grassland areas in the forest category. For local class 3 that represents the settlements and the croplands alongside them, I assumed the presence of biomass from cropland (60%), grassland (29.5%) and forest (15%), because the class is categorised by a mosaic of mixed vegetation and crops, and I derived the proportions based on the heterogeneity of the class. The same proportions were applied at the global land use 30 - mosaic cropland (50-70%)/vegetation (grassland/shrubland/ forest) (20-50%) - assuming a similar distribution, to have a comparison between the two different land use classifications). See Table 2 and Table 5 for land use classes' characterisation.

Table 4. Proportions of total living biomass obtained through the four regression equations reported in Table 3, applied in each land use class.

		Eq. forest	Eq. grassland	Eq. shrubland	Eq. cropland
Global land use classes	14	-	15%	-	85%
	20	15%	29.5%	-	60%
	30	45%	28.5%	-	40%
	60	100%	30%	-	-
	110	30%	58%	30%	-
	130	-	30%	100%	-
	150	30%	79%	-	-
Local land use classes	1	100%	30%	-	-
	2	45%	18.5%	-	40%
	3	15%	29.5%	-	60%
	4	20%	60%	-	20%
	5	-	15%	-	85%
	6	-	50%	-	-
	7	-	50%	-	-
	9	10%	93%	-	-

To obtain the carbon content the final dry total living biomass (t ha^{-1}) values were multiplied by 0.475 (Magnussen and Reed 2004).

3.4.3. Carbon from dead organic matter

The amount of carbon from dead organic matter was derived from the Net Primary Productivity (NPP) downloaded from the MODIS database, that considers a period range of 2000-2015, assuming that the system was in equilibrium (MOD17A3, *http://www.ntsg.umt.edu/project/mod17*).

3.5. Statistical analysis

Because of the different resolutions of the input data, each input map was resampled using a nearest neighbour resampling algorithm at 250 m and at 30 m for the global and the hybrid dataset, respectively.

The “global” and the “hybrid” datasets were compared to highlight possible advantages or limitations and implications in mapping carbon storage and sequestration using different scales and resolutions.

The following steps were used in the analysis:

- since the resolution of the global and hybrid modelling results were 250 m and 30 m, respectively, the results of the hybrid modelling were resampled at 250 m resolution using a nearest neighbour resampling algorithm in order to compare the two sets of results;
- zonal statistics (mean, median and sum) at land use and at sub-catchment level were obtained (see Appendix A on how the sub-catchments were derived). Sub-catchment represents a useful geographical unit for conservation or management strategies implementation at a local decision-making process because hydrologically self-contained;
- linear regression models between “global” and “hybrid” modelling results were run both at pixel and at sub-catchment spatial resolution;
- global and hybrid modelling results were also compared through a test for association between paired samples and using the Kendall correlation coefficient (rank correlation analysis);
- the spatial distribution at pixel and at sub-catchment level was also represented through the qq-plot (quantile-quantile plot), a graph where the quantiles of two distributions (e.g. global and hybrid results) are plotted against each other. If both sets of quantiles come from the same distribution, the qq-plot will show a set of points forming an approximately straight line.

3.6. Software used

Carbon storage and sequestration was calculated using Quantum GIS and GRASS GIS open source software (GRASS Development Team 2017; Quantum GIS Development Team 2017).

R CRAN (R Core Team 2017) open source software was used for the statistical analysis. The packages used were: “raster” (Hijmans 2015), “rgrass7” (Bivand 2015), “rasterVis” (Perpiñán-Lamigueiro and Hijmans 2013).

4. Results

4.1. Local land use classification

Fig. 3 shows the final local land use map derived through the supervised classification and subsequent manual modification using Google Earth® images as background (see Section 3.1). Table 5 shows the local land use classes' description and an approximate correspondence with the global land use cover classes (see for comparison Table 2).

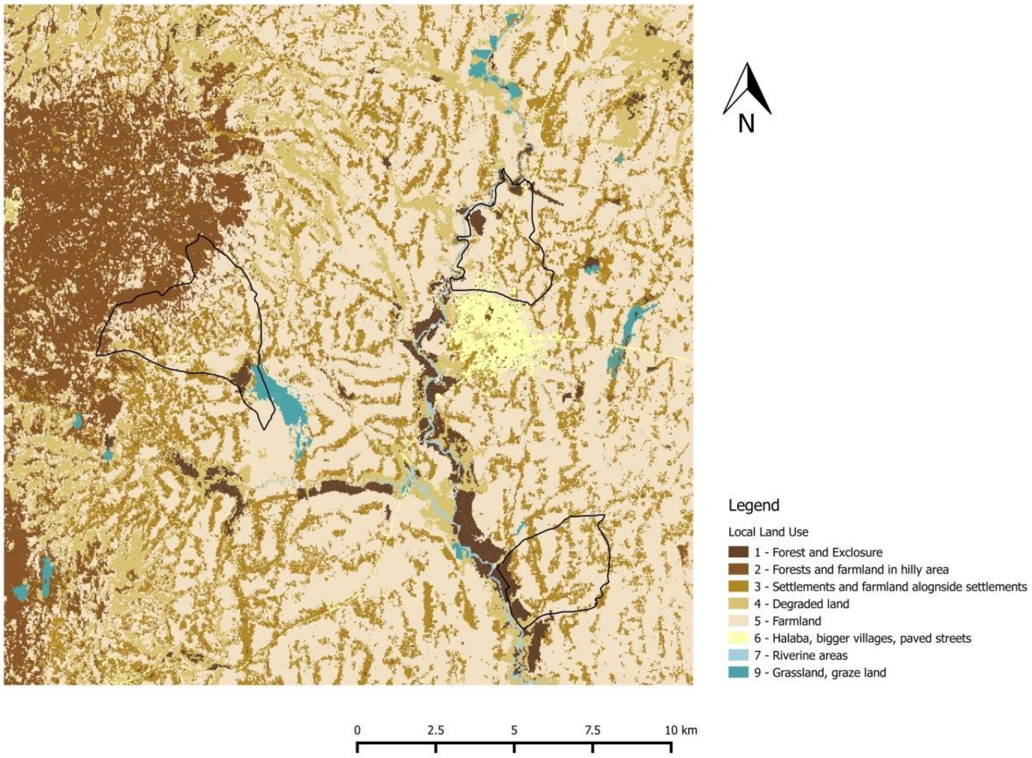

Figure 3. Local land use classification.

Table 5. Local land use classes' description. See Table 2 for corresponding global land use classes' description.

Class Local LU	Corresponding global LU class	Description	Percentage of study area (%)
1	60	Forests and exclosures in the riverplain	2.5
2	30	Forests and farmland in hilly area (mixed semi-natural and agricultural areas)	13.4
3	20	Settlements and farmland alongside settlements	18.7
4	NA	Degraded land	9.5
5	14	Farmland	53.0
6	NA	Halaba, bigger villages and paved streets	1.5
7	NA	Riverine areas	0.6
9	NA	Grassland, graze land	0.8

4.2. Carbon storage and sequestration modelling

The carbon storage and sequestration ranged from 56 to 134 t ha^{-1} with a median of 76 t ha^{-1} estimated from global data, and from 4 to 118 t ha^{-1} with a median of 44 t ha^{-1} in the hybrid case. The linear regression models between the two distributions showed good correlation at sub-catchment level (tons per sub-catchment) with R^2 of 0.96 (intercept of 53.9), while the R^2 decreased to 0.40 at pixel level. Although, the R^2 of the linear regression models between the two sets of results was 0.53 if the median per sub-catchment in t ha^{-1} is considered.

Furthermore, the two modelling results showed fair rank correlation at pixel level with rank correlation coefficient of 0.416, while they showed good rank correlation (τ=0.930) at sub-catchment level if the total amount of carbon storage (t) per sub-catchment is considered. The rank correlation coefficient decreased at 0.43 if the median amount of carbon storage and sequestration (t ha^{-1}) is considered.

The maps in Fig. 4 show the carbon storage and sequestration spatial distribution obtained using the global dataset (4a), and the hybrid dataset (4b). The hybrid modelling results showed more spatial variability, as well as lower carbon stock (t ha^{-1}) in the whole area. This aspect is quite clear from the density plot in Fig. 5; the graph shows how the two result distributions (global and hybrid) differed in the estimates range and in the variability. The distribution of the global modelling results (in blue) showed overall higher estimated and lower variability as compared to the distribution of the hybrid modelling results (in red).

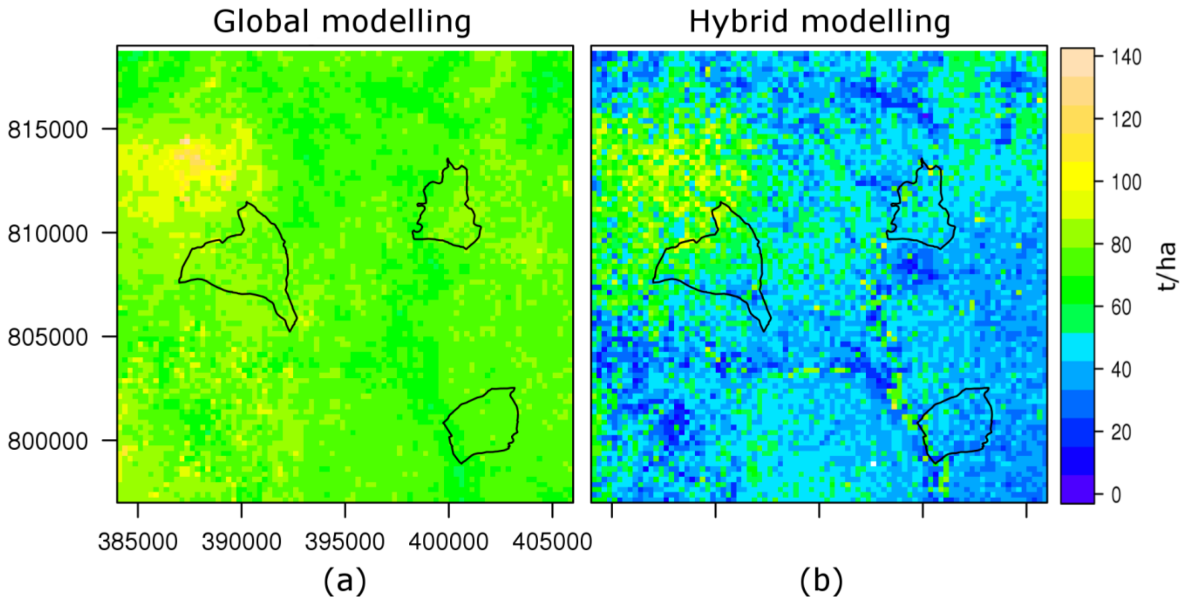

Figure 4. Carbon storage and sequestration (t ha^{-1}): a) global modelling results; b) hybrid modelling results.

The lower estimates of carbon stock in the hybrid modelling are shown also in the qq-plots in Fig. 6 both at pixel resolution (6a), and at sub-catchment resolution (6b). At pixel resolution (Fig. 6a) the difference between the quantile of the distribution of the hybrid and global modelling results was high especially at lower estimates. This means that lower carbon storage and sequestration values are more overestimated by the global modelling than higher carbon storage and sequestration values, if the hybrid modelling results are used as reference. The difference between the quantiles of the distribution decreased at higher estimates showing better correlation at high estimates. Moreover, also at higher quantiles the qq-plot at pixel level (Fig. 6a) shows that the global modelling obtained higher values of carbon storage and sequestration. At sub-catchment resolution (Fig. 6b) the difference remained constant throughout the quantiles, with lower estimates in the hybrid modelling.

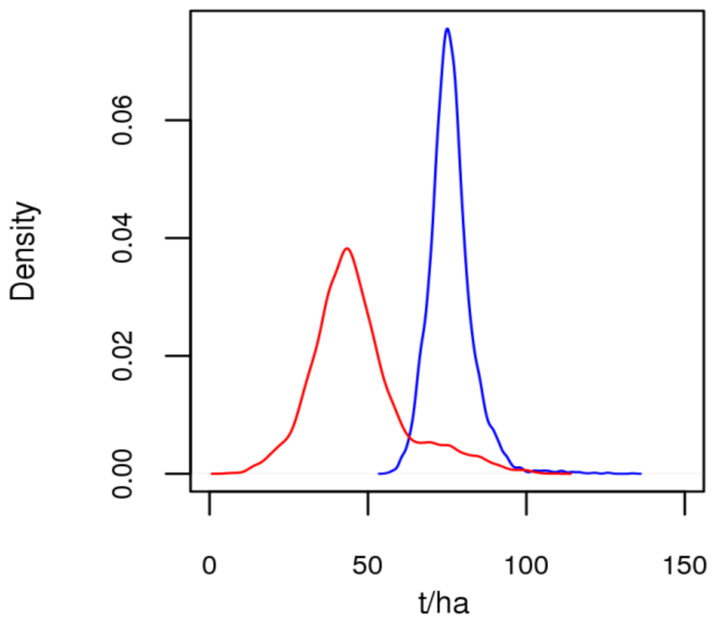

Figure 5. Density plot of the global (blue) and the hybrid (red) modelling results.

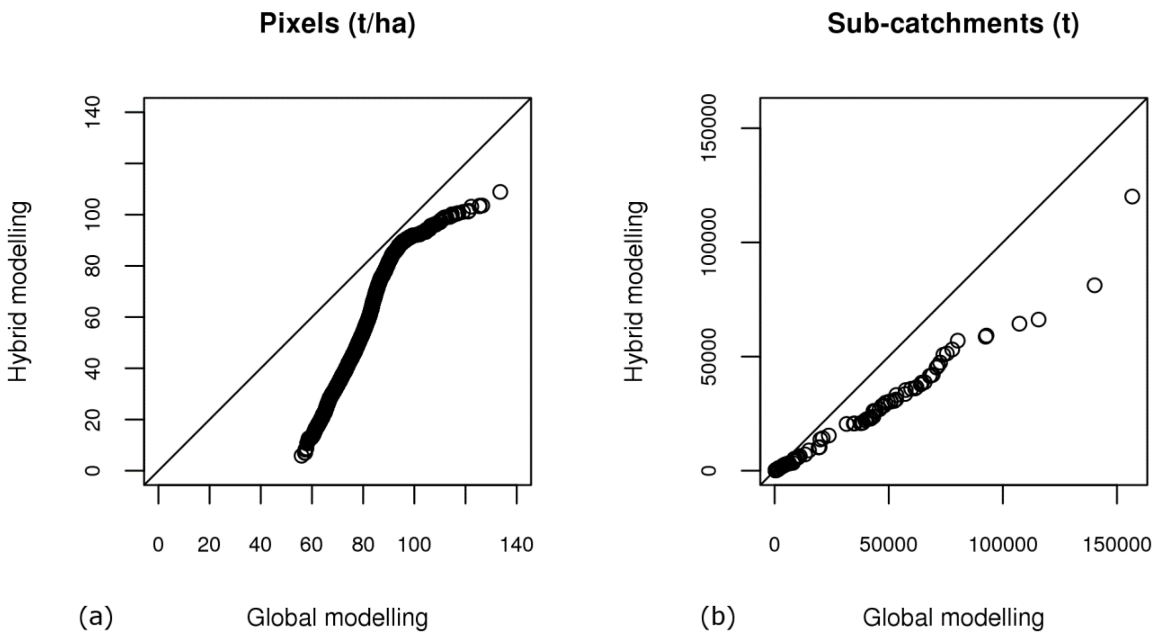

Figure 6. qq-plot between the global results and the hybrid results of carbon storage and sequestration at pixel level (a) and sub-catchment level (b).

The histograms in Fig. 7 show the median value of carbon storage and sequestration (t ha^{-1}) summarised by global (a) and local (b) land use classes. In blue are shown the results obtained using the global dataset, and in green are shown the results obtained using the hybrid dataset. The higher estimates by the global modelling at pixel level (Fig. 6) are also confirmed at land use level; in fact, the blue bars are in the all land use classes higher compared to the green bars. The median value of carbon storage and sequestration (t ha^{-1}) per local land use class (Fig. 7b) was higher in the class 2 in both the global and the hybrid modelling. Class 2 of the local land use corresponds to cultivated area with semi-natural vegetation and agroforestry practices in the western hilly areas (see Section 3.1). Its median carbon storage was also higher compared to the median carbon storage and sequestration estimated for the class 1 that represents the forests and exclosures especially in the river banks, that before the restoration activities were degraded land.

Apart from class 60 (open (15-40%) broadleaved deciduous forest/woodland (>5m)), that is represented by a very small area (~0.1% of the whole area), there was lower variability of carbon stocks estimates among land use classes if the global dataset was used as compared to the estimates of the hybrid modelling (Fig. 7).

Among median estimates of the global and local land use classes that can be compared, percentage differences in the range of 21%-50% were found, with higher values in all cases in the global estimates (see Table 6). For details on the corresponding land use classes see Table 2 and Table 5.

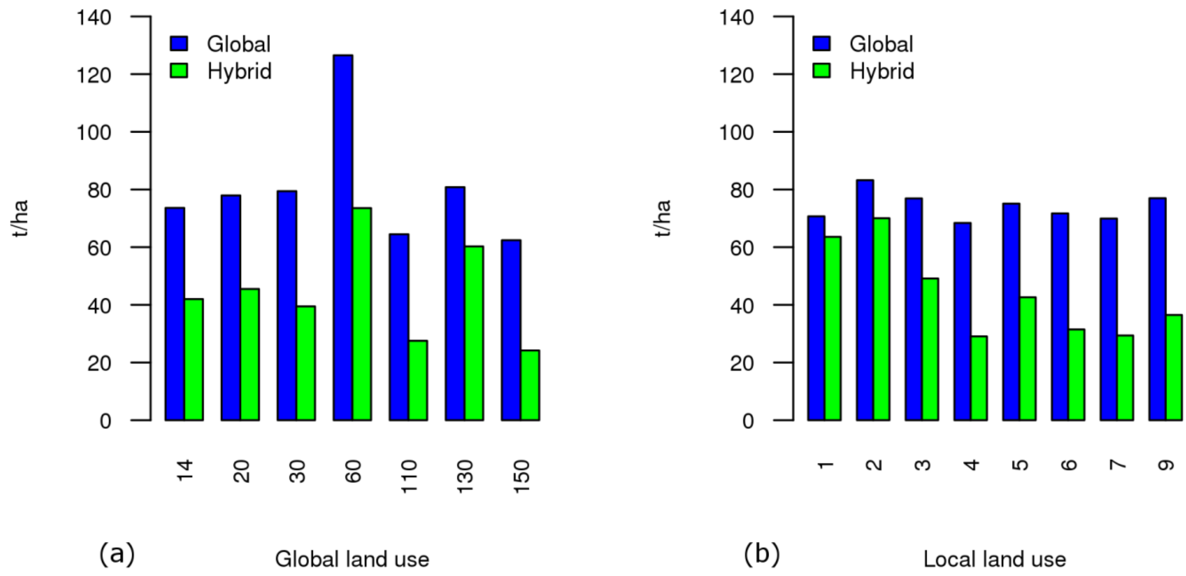

Figure 7. Histograms of median carbon storage and sequestration (t ha-1) per global (a) and local (b) land use classes. In blue the results obtained using the "global" dataset and in green the results obtained using the "hybrid" dataset.

Table 6. Median values per corresponding global and local land use classes that were obtained using the global dataset and the hybrid dataset. The last column shows the percentage difference obtained using the two datasets if the corresponding global and local land use classes are considered.

Brief LU description	Global LU		Local LU		% difference
	Class	Median (~ha t^{-1})	Class	Median (~ha t^{-1})	
Farmlands	14	74	5	43	42%
Farmlands and mixed semi-natural vegetation	20	78	3	49	27%
Mixed croplands and vegetation	30	79	2	70	21%
Forests	60	127	1	64	50%

5. DISCUSSION

5.1. Carbon storage and sequestration modelling

It should be borne in mind that this type of carbon storage and sequestration modelling is not dynamic, rather it just considers carbon static pools without addressing the dynamics between the different pools, leading to an oversimplification of the carbon cycle. However, this limitation does not affect the validity of the comparison being studied here.

The fair correlation at pixel level and the difference estimates of carbon storage and sequestration (see Fig. 4 and 5) between global and hybrid modelling was mainly due to i) the different source of SOC that was considerably lower in the local sample compared to the ISRIC soil organic carbon dataset, and to ii) the different land use datasets used to calculate the biomass distribution as summarised in Table 3 and 4.

The SOC estimates derived from the ISRIC dataset and used in the global modelling ranged from 50 to 160 t ha^{-1}, with a mean of 63 t ha^{-1}. The SOC derived from the interpolation of local samples data and used in the hybrid modelling ranged from 0 to 84 t ha^{-1}, with a mean of 31 t ha^{-1}. From these results, it can be asserted that the ISRIC SoilGrid 250m overestimates the SOC in the study area.

In Ethiopia, few studies tried to estimate total carbon storage of rural ecosystems. Most of the studies focused their attention just on soil carbon stock because of its high importance on soil fertility (Girmay et al. 2008; Rimhanen et al. 2016). However, previous studies on carbon storage in Ethiopia found higher amount of above and belowground carbon stocks as compared to this study results (both global and hybrid modelling results). Vanderhaegen et al. (2015) found a total carbon stock density of ~70±12 t ha^{-1} in maize field ecosystems, ~77±10 t ha^{-1} in grazing lands, and up to 337±121 t ha^{-1} in natural forest and coffee agroforestry areas. De Beenhouwer et al. (2016) estimated a total carbon stock ranging from 219±23 t ha^{-1} to 413±56 t ha^{-1} in an agroecosystem dominated by natural forest, coffee extensive cultivations and more intensive agroecosystem and intensified shade plantation systems. Both the studies are, however, representative of a more natural and forested ecosystem as compared to the Halaba rural area. Bajigo et al. (2015) reported a carbon stock of 51±0.7 t ha^{-1}, 86±20 t ha^{-1}, and 448±43 t ha^{-1} in home gardens, parklands and woodlot, respectively.

This study results were closer to the studies on agricultural areas (Vanderhaegen et al. 2015; Bajigo et al. 2015). In fact, the study area is characterised by large croplands with small patches of natural vegetation. Furthermore, many forest areas (especially exclosures) are located in former degraded land now designates to restoration purposes, therefore their soil carbon stock is still scarce as proved by the local sample analysis. Land degradation is yet considered one of the main causes of soil carbon depletion (Lal 2004a; Lal 2015). Land degradation issue is well known to lead to a reduction of carbon storage and sequestration, and to an increase of greenhouse gas emissions (Lal et al. 2012; Stavi and Lal 2015). In the study area, land degradation is recognised as a serious issue and restoration programs have been already launched and implemented (Byg et al. 2017; Getnet et al. 2017).

The lower carbon storage and sequestration estimated in both the global and the hybrid modelling as compared to the aforementioned studies could also be the results of using the NDVI as a proxy of the biomass. In fact, the biomass was calculated using max NDVI that was derived from Landsat images of dry periods (see Appendix A and Section 3.4.2). This aspect could have influenced this study estimates. Furthermore, for the hybrid modelling the biomass calculation was influenced by the low extension of forest and by the large distribution of degraded lands and farmland areas. Moreover, the Ethiopian studies (Bajigo et al. 2015; Vanderhaegen et al. 2015; De Beenhouwer et al. 2016), used to compare this study results, estimated the carbon from living biomass through field measurements, and average or species-specific wood density.

Another factor that could have affected this study results was that the SOC stock was calculated for 20 cm of soil depths (see Sections 3.2 and 3.4.1), while in most of the other studies a standardised soil depth of 30 cm was used. This aspect could have resulted in lower SOC estimates in both the global and the hybrid modelling, leading to lower estimates of carbon storage and sequestration.

5.2. Implications of mapping at different scales and resolutions

In order to accommodate the resolution of the inputs data, the carbon storage and sequestration modelling returned results at 250 m resolution, or at 30 m resolution using either the global dataset, or the hybrid dataset, respectively. The coarser scale resolution of the global data likely led to oversimplification and inaccuracy on the carbon storage and sequestration estimates that could be a key issue if the assessment aims to support decision-making and planning processes (Pandeya et al. 2016). Accordingly, the usability of carbon stocks assessments depend on aims and especially on the scale of intervention to restore carbon stock (e.g. field, *kebele*, sub-catchment or national scale).

In this study, the carbon storage and sequestration returned very different estimates using global or hybrid datasets (see Fig. 5 and 6). The carbon stock was lower in the hybrid modelling, whereas higher estimates were obtained in the global modelling.

The median of the whole study area of hybrid results was ~40% smaller than the median of global results. Therefore, if global datasets are used, decision-makers might not give the strong attention that carbon storage and sequestration should have. For example, areas having low carbon stocks (i.e. carbon stocks lower than 50 t ha^{-1}) would be completely missed by the global modelling analysis (as showed by the qq-plot in Fig. 6a). However, targeting carbon stocks restoration should be a priority strategy in the study area in order to increase soil fertility, and to reduce soil erosion. In fact, the area is known to be highly degraded, therefore, high attention should be given to carbon stocks estimates, which should be the more accurate as possible to highlight the degree of the problem.

Moreover, carbon storage and sequestration obtained using the hybrid dataset showed more spatial variability compared to the global modelling, as it is shown in Fig. 4. Global scale modelling appeared to highly reduce the spatial diversity and variability due to courser data derived from national interpolation (e.g. SOC data from ISRIC SoilGrid 250m dataset), and to less detailed land cover dataset. Therefore, the low spatial detail of the "global" estimates showed that care should be taken when results derived from global datasets aim to be used as local decision-making support. In the absence of dense sampling, this problem is expected to persist even if the size of grid cell of global datasets is decreased. Decision-making strategies, that rely on highly detailed carbon stocks assessments to select and prioritise certain areas for restoration aims, would face difficulties due to the course resolution. Moreover, the global modelling estimated lower spatial variability also at land use class resolution (see Fig. 7) making difficult to select priority land use classes for interventions.

The median carbon storage and sequestration per global and local land use classes was very different depending on the datasets used (Fig. 7). In all the classes of global and local land use, the global modelling estimated higher median carbon storage and sequestration with scarce spatial variability. Accordingly, global modelling proved to be not very useful for selecting priority land use classes for carbon storage and sequestration enhancement purposes, while the hybrid modelling could give better indications on where to intervene for increasing carbon storage and sequestration. The lower variability at land use resolution obtained using the "global" dataset could represent a limitation if the priority is to identify land use classes with low carbon stocks in order to support strategies that will enhance the carbon sequestration both at below and above ground level. Therefore, decision-making processes that aim to target areas with low carbon storage and sequestration might be impractical if the global dataset is used due to the low variability.

However, the rank correlation analysis at sub-catchment resolution showed good correlation with a rank coefficient of 0.930. Therefore "global" datasets proved to be good enough for targeting sub-catchments based on their rank distribution. Prioritisation at sub-catchment level could be obtained using the "global" dataset. These results confirmed the modifiable areal unit problem (MAUP) that underlines the importance of the scale problem and of the zoning (or aggregation) problem in the spatial analysis (Openshaw and Taylor 1979; Jelinski and Wu 1996). Several studies highlighted the importance of the spatial scales or the extents when modelling environmental properties (Poggio et al. 2010; Grunwald et al. 2011; Malone et al. 2013; Cavazzi et al. 2013; Malone et al. 2017). Accordingly, care should be taken because aggregation in different areal units could lead to unreliable findings. This aspects was also highlighted by Grêt-Regamey et al. (2014) who found that ESS mapping is affected by the mapping resolution; coarse resolution was found to reduce spatial pattern information of ESS assessments, especially in less rugged terrains. In our study, the scale dependency of results and the zoning (or aggregation) problem was found even when the median per sub-catchment (t ha-1) was considered; it showed similar results to the rank correlation at pixel level (τ=0.430), thus showing a poor correlation compared to the rank correlation if the sum of carbon storage and sequestration (t) per sub-catchment was considered (τ=0.930).

Apart from the different source of SOC data, also the quality of the global land use classification likely affected the estimates in the global modelling, by introducing possible errors in the biomass calculation that was derived from NDVI, as well as from land use classes' distribution. Hence, a remote sensing approach that enables to classify the landscape should be used to derive a reliable and detailed land use dataset. However, land use classification of remote sensing images was a challenge because of the absence of suitable remote images representative of the vegetation season due to high clouds cover. In the land use classification process, another challenge was posed by the high heterogeneity of the Ethiopian landscape that consists of a mix of small patches of different land uses derived from the long history of smallholder cultivation (Wondrade et al. 2014; Hurni et al. 2015; Eggen et al. 2016). Therefore, the method used in this study to calculate the biomass could have affected the estimates of the carbon derived from above and below ground biomass, using both the global dataset and the hybrid dataset. However, this aspect does not affect the validity of the comparison being studied here. Moreover, the better accuracy of the land use classification derived from the supervised classification (see Section 3.1) likely led to more reliable results in the hybrid modelling.

Considering these results, the study suggests that care should be paid in using global data to assess carbon storage and sequestration, and this study agree with Vihervaara et al. (2012) that stressed how ESS mapping needs detailed datasets to estimate variation at local level that could be relevant at a decision-making perspective. Therefore, based on these results, I recommend, whenever feasible, to integrate global data with local and detailed data to obtain accurate ESS assessments (in this case carbon storage and sequestration) that can support decision-making processes.

Despite the lower variability and the difference in the carbon storage and sequestration estimates by the “global” or the “hybrid” dataset, it was found that the “global” dataset was good in identifying the sub-catchments rank distribution. Therefore, decision-making strategies that aim to target sub-catchments with lower carbon storage and sequestration compared to others sub-catchments could be planned also using data from global datasets. If the aim is, instead, to calculate the precise amount of carbon stocks, this study found that the “global” dataset highly overestimated them in the whole study area, if the “hybrid” results estimates are used as reference. In conclusion, the global datasets proved to be good only to target sub-catchments, for more details assessments it was found that local data were necessary.

5.3. Land degradation risk and possible "carbon interventions"

This study results showed that carbon stocks in the study area were substantially low especially according the hybrid case. However, the study area could have potential in enhancing carbon sequestration, if degraded areas were considered for restoration purposes by, for example, adopting the REDD+ (Reducing Emissions from Deforestation and forest Degradation, "plus" afforestation) mechanism, a tool that supports and incentivises forest carbon-enhancing approaches in order to reduce deforestation rates and greenhouse gases emissions. Ethiopia started adopting the REDD+ mechanism from the 2006 (Gonzalo et al. 2017) and carbon sequestration started gaining more attention.

Another mechanism that could help in restoring carbon stock is to implement at local level the 4 per mille initiative. The 4 per mille initiative, also called 4 per Thousand (Minasny et al. 2017), aims to increase global soil organic carbon content by 0.4% per year, as a compensation for global greenhouse gases emissions originated by anthropogenic activities, as well as to restore soil quality, and promote food security (Lal 2016; Minasny et al. 2017). Considering that this study results showed that the study area is characterised by low carbon stock, policies could support the implementation of the 4 per mille proposal.

Furthermore, emphasis should be given to the key role of crop residues in enhancing SOC in farmland areas (Lal 2006; Girmay et al. 2008; Lal 2008; Lal 2015). Besides, crop residues retention is also indicated as an important measure in order to enhance SOC content to reach the 4 per mille target (Minasny et al. 2017). Due to the high distribution of croplands in the study area, decision-making strategies should incentivise a sustainable agriculture where crop residues are retained after the harvest, in order to increase carbon stocks, and therefore enhance soil fertility. The application of manure could also increment soil organic carbon and increase soil quality. Manure application is often indicated as measure to reduce land degradation and increase carbon sequestration (Lal 2004b). However, in Ethiopia, manure application is often limited due to the shrinking number of cattle per household, the transport constraints, and the habit of using it as fuel (FAO 1986; Desta et al. 2000; Gebreselassie 2006). Therefore farmyard manure application is usually limited to the homestead farm (Amede et al. 2001; Haregeweyn et al. 2008; Girmay et al. 2008). Moreover, livestock through manure production supports soil organic matter enhancement in a certain area, by removing it from another area through grazing. Therefore, a sustainable management at landscape level is necessary in order to secure the production of benefits in a certain area, without producing disservices and harmful effects in other areas.

In conclusion, both the global and the hybrid modelling found higher carbon storage and sequestration in the western hilly area (see Fig. 4) that is characterised by a mix of agroforestry, woodland and farmland patches. Maintaining or enhancing the benefits of the carbon storage and sequestration in the area should be a key policy target. Accordingly, another suggested intervention could be the implementation of afforestation and agroforestry practices, especially in the flatter areas that are mainly characterised by croplands.

The implementation of the suggested activities, interventions, and measures must be planned bearing in mind the importance of securing the generation of inclusive benefits by integrating new incentives and development strategies (MEA 2005). However, in poor areas such as the Halaba *woreda*, individual households often fail to take into account possible long-term benefits from restoration interventions (such as the 4 per mille and especially the REDD+ mechanisms) because their survival depends on more immediate and locally important services, such as availability of firewood, fodder and thatch grass. The study of Byg et al. (2017), that evaluated distribution of services and disservices of three restoration areas (exclosures) in the same study area, found that such restoration programs often fail to couple conservation efforts with development goals aiming to increase livelihoods, generate well-being and overall alleviate poverty.

If these aspects are not strongly borne in mind there is the risk to undermine the restoration activities and benefits (MEA 2005). Byg et al. (2017) stressed that ecosystem services-based restoration approaches should be combine with poverty eradication strategies by taking into account benefits and dis-benefits, as well as trade-offs between different services and/or between groups of people.

6. CONCLUSIONS

My results suggested that intensive restoration activities should be planned and implemented in the area in order to enhance carbon storage and sequestration, as well as to reduce soil erosion, a key driver of soil organic carbon depletion. The implementation of successful restoration measures can be address only if priority areas are selected through modelling and mapping processes.

Land degradation assessments, or in this case carbon storage and sequestration assessments, need to be reliable and accurate if they aim to characterise the landscape in order to identify sustainable restoration measures. This aspect is particularly important when these assessments are used at a decision-making level. Even though this study found that global data were not accurate to estimate absolute carbon storage and sequestration, global datasets proved to be suitable for addressing carbon stocks at sub-catchments ranking level. Therefore, depending on the scope or scale of the assessment, this study suggested that care should be used when using global datasets to inform decision-making strategies, keeping in mind possible inaccuracies with the estimated values.

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CHAPTER 4

Using a participatory approach to infer land degradation causes and consequences at different knowledge levels

1. INTRODUCTION

In order to take into account and acknowledge the complexity of land degradation risk, in this study, a participatory approach that represents an effective method for gaining and addressing local knowledge and perspective was used. Participatory methods started gaining interest in the 1980s with the development of the Rapid Rural Appraisal (RRA) (Chambers 1981). Subsequently, in the 1990s, the RRA evolved in the Participatory Rural Appraisal (PRA) (Chambers 1994a; Chambers 1994b; Chambers 1994c; Cornwall and Jewkes 1995), “a family of approaches and methods to enable rural people to share, enhance, and analyse their knowledge of life and conditions, to plan and to act” (Chambers 1994c).

Participation of local communities in the study of complex systems and aspects enables to achieve local environmental knowledge and experiences, and to integrate scientific and quantitative data with local qualitative data (Whitfield and Reed 2012), to achieve comprehensive and effective assessments that can be used for addressing environmental management strategies (Cornwall and Jewkes 1995; Reed et al. 2007; Reed 2008; Raymond et al. 2010). Participation of local communities facilitates social learning (Pretty 1995; Reed et al. 2007; Romina 2014), sharing of knowledge and experiences (Goulet 2013; Bautista et al. 2017), as well as empowerment of local stakeholders and communities (Chambers 1997; Mosse 2001; Mayoux and Chambers 2005). This approach enables local communities to share their own social, political, cultural and economic context and perspective in relation to how it affects their well-being (Whitfield and Reed 2012). Participation methods are also important for gathering local knowledges and experiences that can be used for supporting decision-making processes (Reed 2008; Hage et al. 2010; Luyet et al. 2012; Bautista et al. 2017). Local communities engagement is crucial when aiming to achieve the adoption of a sustainable and adaptive management of natural resources (Cundill and Fabricius 2009; Leys and Vanclay 2011).

Capturing local knowledge is, therefore, highly important to address complex issues such as land degradation risk, and identify the major aspects involved in the system. Exploring farmers’ experiences and perspectives constitutes a necessary approach when aiming to achieve a comprehensive assessment of agroecosystems and their different aspects (Stringer and Reed 2007; Dolinska and d’Aquino 2016).

The principal aim of this study was to understand land degradation in order to help halting it by involving communities of three different *kebeles* (counties), and the experts of the Halaba Agricultural Office. The main objectives of this study were to: i) identify causes, trends and consequences of land degradation, ii) identify the major consequences of the population growth, iii) assess which are the aspects that determine resilience to land degradation, and how different wealth categories are affected by land degradation, and iv) identify coping strategies that could alleviate land degradation and poverty. This study could be useful to inform decision-making processes that aim to reduce and reverse land degradation patterns keeping in mind local priorities and local economic development.

2. METHODS

This study targeted the communities of the three *kebeles* (Andegna Choroko, Layignaw Arsho, and Asore), and the Agricultural Office's experts in the Halaba special *woreda*. During the summer 2016, I conducted a participatory approach in order to gain local perspective on land degradation risk in the three *kebeles*.

To infer land degradation causes and consequences and the overall issue of land degradation, the participatory approach was divided in 5 main objectives. In Table 1 the participatory approach's objectives are described and in Table 2 the methods used in order to address each objective previously identified, for each *kebele*, are presented.

The participants were selected with the help of local facilitators using a list of households derived from a previous participatory study in the same *kebeles* (Byg et al. 2017).

In the focus group discussions (FGDs), the participants were divided by gender. This aspect facilitated the participation of women, that usually is constrained by their fear of express their self and to share their opinions in front of male head households (Chambers 1994b; Evans et al. 2006; Corbett 2009).

Table 1. Description of the objectives of the participatory approach carried out in the summer 2016.

Objective	Main topic	Objective's description and characterisation
Objective 1	Land degradation - Conservation measures – Livelihoods	1a. Identify the main drivers of land degradation. 1b. Identify the consequences of land degradation. 1c. Are there some solutions or conservation measure that could help reducing land degradation and alleviate poverty? 1d. Identify livelihoods affected by land degradation.
Objective 2	Population	2a. What are the reasons of the current population growth trends? Identify past trends that led to increase in population pressure. 2b. Identify causes and consequences of population growth.
Objective 3	Scenario construction	Try to identify and construct four plausible scenarios given certain trends on population pressure, climate, and land management (for further details see Chapter 5).
Objective 4	Land tenure	4a. Identify the land tenure system. 4b. Assess the role of land tenure system in land degradation trends and in land management.
Objective 5	Young's future ambitions	Identify young's hopes and ambitions for their future. Are there other job opportunities apart from farming activities?

Furthermore, based on previous work on participatory wealth ranking exercise (Byg et al. 2017), I was able to select the participant based on their wealth status (i.e. poor, medium, and rich). This was important to gain knowledge and perspective of different wealth groups in the three *kebeles*' communities. This method helped to derive if and how different wealthy categories were affected by land degradation. Therefore, in each FGD, each wealth category was represented. Higher participation of the poor category was adopted because it was the most represented wealth category in all the *kebeles*. Medium was also more represented as compared to the rich wealth category. Therefore, generally more medium wealth households where represented during the FGDs as compared to the rich wealth households. Hence, in a FGD with 7 participants usually 4 participants were from poor households, 2 participants were from medium households, and 1 participant was from a rich household. Not always it was possible to maintain this proportion, therefore for some FGDs some compromises were adopted. For objective 1 (e.g. land degradation causes and consequences, soil and water conservation measures and livelihoods), for each gender, two FGDs were conducted to elicit together medium and rich wealth categories, and in a separate FGD only poor wealth category (see Table 2).

Table 2. Summary of activities carried out for each *kebele* (Andegna Choroko, Layignaw Arsho and Asore). SWC measures: soil and water conservation measures; M/R: Focus Group Discussion (FGD) that elicited only households of the rich and medium wealth status; P: FGD that elicited only households of the poor wealth status.

Objective/Topic	Small FGD		Single interview	
	Male	Female	Male	Female
1. Land degradation; SWC measures; Livelihoods	1 M/R 1 P	1 M/R 1 P	-	-
2. Population	1	1	-	-
3. Scenarios construction	1	1	-	-
4. Land tenure system	-	-	5	5
5. Young's future ambitions	1	1	-	-
Total per *kebele*	**5**	**5**	**5**	**5**

The objective 3 (i.e. scenarios construction) envisaged a participatory exercise where participant, divided in two groups, were asked to draw possible scenarios based on certain trends (on population pressure, climate change, and land management) previously illustrated. The number of participants was in a range of 8-9. Each group was constituted by 4 or 5 participants (with minimum 2 poor households represented; usually 2 poor, 1 medium and 1 rich). The scenarios developed were four; each group of participants developed two scenarios. Table 3 describes the trends illustrated to the participants before starting the scenario construction's exercise. Refer to Chapter 5 for further details on the scenario construction objectives and on its main findings.

Table 3. Description of the parameters considered in the four scenarios developed during the FGDs. Based on these patterns the participants drew plausible scenarios to individuate the consequences of climate, population, and land management at their *kebele* level.

	Parameters		
	Climate	**Population**	**Land management**
Scenario A	Changes projecting forward the actual patterns of climate change	Continues growing	Steady – no changes from actual land management
Scenario B	Changes projecting forward the actual patterns of climate change	Stabilises	Increase in conservation measures implementation
Scenario C	Stabilises	Continues growing	Increase in conservation measures implementation
Scenario D	Changes projecting forward the actual patterns of climate change	Continues growing	Increase in conservation measures implementation

Objective 4 (i.e. land tenure systems) was elicited using semi-structured single interviews. Yet, land tenure system objective was addressed through the single interview method because it is a delicate aspect and argument that is not indicated to be debated in a focus group discussion. For each *kebele*, 6 poor, 2 medium, and 2 rich households, equally divided by gender, were interviewed.

For objective 5 (i.e. young's future hopes and ambitions) young between 15 and 18 years of age were selected. The households were identified, and the sons and daughters were asked to participate at the FGDs. Also in this case, the participants were divided by gender, and all the three wealth categories were involved.

In order to elicit another level of knowledge, the same objectives, apart from objective 5 (i.e. young's hopes and ambitions), were addressed with some experts of the Halaba Agricultural Office through semi-structured interviews and focus group discussions. Table 4 shows the summary of the activities carried out with the experts of the Halaba Agricultural Office.

Table 4. Summary of the activities that involved the experts of the Halaba *woreda* Agricultural Office. FGD: Focus Group Discussion; SSI: Semi-Structured Interview.

Objective/Topic	**Activities**	**Participants**
1. Land degradation;	FGD	5
1c. SWC measures	FGD	3
2. Population	SSI	1
3. Scenarios construction	FGD	5
4. Land tenure system	SSI	1

For more detailed information about the semi-structured interviews, and the focus group discussions refer to the developed participatory approach protocol in Appendix B, where the questions posed to the participants and the methods used are reported for each objective. The number of participants at the FGDs and interviews with the communities, divided per gender, wealth category, and age range (adult or young) are indicated in Table 5. In Appendix C, Tables C.1, C.2, and C.3 show the number of participants per wealth status categories, per FGD, and per objective inferred in each *kebele*.

Table 5. Total number of participants at the FGDs and interviews conducted with the communities per age range, gender, and wealth category (R: Rich; M: Medium; P: Poor).

Activities	Adults		Young	
	Male	**Female**	**Male**	**Female**
FGDs	14 R 25 M 40 P	16 R 22 M 43 P	3 R 3 M 10 P	2 R 3 M 12 P
Interviews	3 R 3 M 9 P	3 R 3 M 9 P	-	-
Total	190		30	

The sample size of the participants was justified from literature review on participatory studies. The recommended participants' sample size ranges from 20 to 60 according several studies on participatory and qualitative studies (Morse 2000; Creswell 2007; Dworkin 2012). The sampling procedure in qualitative research is indeed more flexible than the one needed in quantitative studies (Coyne 1997). Moreover, the sample size of qualitative researches is usually smaller than the one used in quantitative researches (Dworkin 2012). The sample size of this study enables to reach saturation and redundancy, and it was selected based on the study's purpose and aim, on the research time, budget and resources (Patton 1990).

2.1. Software and other instruments used

In order to elicit communities' knowledge, local as well as external facilitators were necessary. The local facilitators (usually developing or extension agents) helped during the selection of the participants and in organising the different sessions. They were essential also for translating from the Halaba local language to the Ethiopian national language, Amharic. Hence, external facilitators (University of Hawassa researchers) were essential to facilitate the discussions and the interviews, and to translate the discussion from Amharic to English. Notes in English were taken for each question answered, and subsequently copied in a digital format. Additionally, discussions were also audio-recorded to enable a second listening process in case of unsure or unclear patterns.

The use of semi-structured interviews and FGDs was justified by the necessity of having a predefined structure due to the double-translation process. Other participatory approach methods with a more open structure would have been more complicated to facilitate. In fact, an open structure would have requested major involvement of the local facilitators, whereas a semi-structured approach enabled an instantaneous translation and follow-up discussion. This method allowed me to participate and facilitate the discussions.

Moreover, the use of more participative approaches and methods (such as problem tree and spider diagrams, or ranking exercises; e.g. Slocum (2003), Bradley and Schneider (2004), Durham et al. (2014)) to infer the different objectives was constrained by the allocated time, but especially by the low literacy rate of the rural communities. In fact, these participatory methods would have been problematic to facilitate because several communities' participants were not able to express themselves in Amharic, and the majority could not write and read Amharic.

For objective 3 (e.g. scenario construction) flip charts and coloured pens were also used. After the exercise (e.g. drawing possible and plausible scenarios), the participants were asked to justify their thoughts and the patterns represented in the drawings, and notes where taken about each scenario. This objective can be described as a participatory mapping where participants could express their knowledge and ideas with an interactive framework to facilitate creative local knowledge sharing.

The transcriptions of the interviews and FGDs were subsequently uploaded in the R tool for qualitative data RQDA (Huang 2014), where they were codified using several main topics (e.g. land degradation, land tenure system, education, policy, population pressure, land management, climate). Within each of these code's categories, more specific topics were codified (e.g. for land degradation: land degradation types, land degradation causes, land degradation consequences, land degradation and poverty, resilience to land degradation, etc.). The codes were identified according a pre-defined coding structure based on the main research questions, and they were subsequently sub-divided in more specific categories derived from the analysis of the data collected.

Main patterns were derived after the coding process mainly using a qualitative approach (Dey 1993). Text mining was also used to identified trends on some of the main objectives of the participatory approach. Text mining, also known as Text analytics, is used to analyse qualitative data, such as text of interviews as well as emails, books, or social media, using a quantitative and statistical approach. Text mining transforms the unstructured text into structured data for identifying and extracting facts, relationships and assertions that could otherwise remain buried in the mass of textual unstructured data (Hearst 1999; Feldman and Sanger 2006). Text mining constitutes a set of approaches to derive quantitative information from qualitative data. These approaches are often used in economic and social science, health researches, and political studies (Cao et al. 2011; Mostafa 2013; He et al. 2013; Spasić et al. 2014; Khadjeh Nassirtoussi et al. 2014; Younis 2015)

In this study, using the Text mining techniques, some of the text derived from the codes previously identified were processed to remove noise, commonly used words, and stop words. A matrix of words and their frequencies was obtained. Classification and association rules were then used to identify patterns in the text. These patterns were shown using word clouds and bar plots. More specifically, correlation analysis among words were used. Patterns were also shown using word cloud's plot and bar plots to highligh the words frequency in different texts previously processed. R CRAN (R Core Team 2017) open source software was used for the statistical analysis using text mining processes. The main packages used were: "tm" (Feinerer et al. 2008), and "wordcloud" (Fellows 2014). In this study, these methods were used to justify some of the patterns found using merely qualitative approaches.

3. RESULTS

3.1. Land degradation in the three *kebeles*

3.1.1. Causes of land degradation

Different aspects were identified causing land degradation in the three *kebeles*. In the Asore *kebele*, the land degradation was particularly felt; participants asserted that the degradation involves the majority of the *kebele*. They pointed out that "*there are no places not degraded yet*". By land degradation farmers meant different types of wind and water driven soil erosion; from sheet erosion, removal of top soil, to the large gullies formation.

The local communities acknowledged the presence of various direct and indirect drivers of land degradation exacerbation. Improper land management, lack of soil and water conservation (SWC) measures implementation, deforestation and lack of vegetation cover, geomorphology (e.g. steep terrain), free grazing, overexploitation of natural resources, and weather conditions (e.g. strong and erratic rainfalls, droughts) were direct factors affecting land degradation pointed out during the different discussions. Fig. 1 shows the frequency of the ten mostly used words of the text previously codified to infer the "land degradation causes" objective in the three *kebeles* (Asore (a), Layignaw Arsho (b), Andegna Choroko (c)) and the Agricultural Office (d). The frequency of the words highlights the importance of some aspects such as erosion, poverty, flood, population, deforestation.

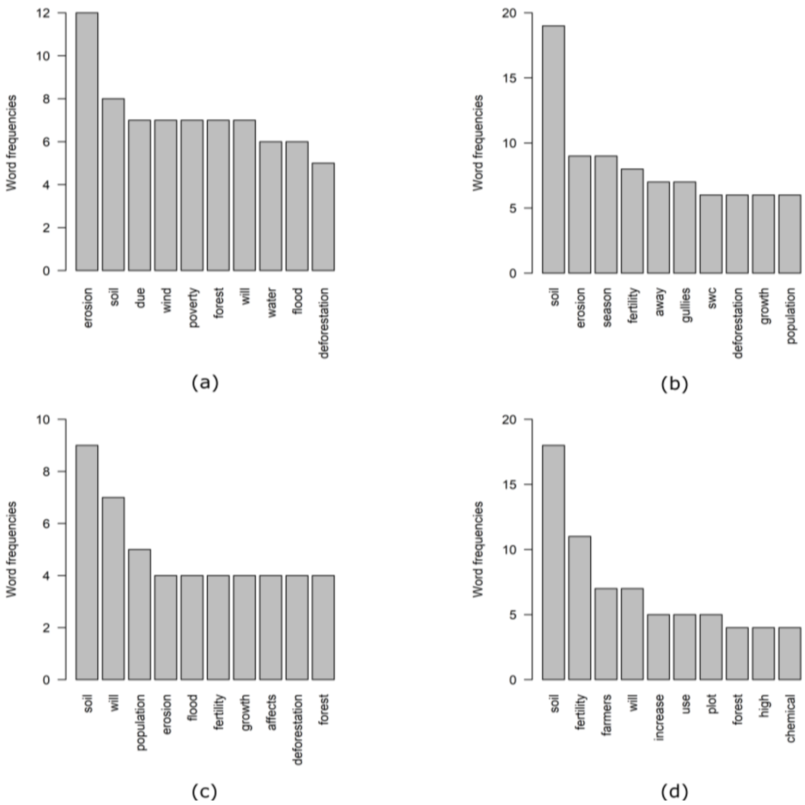

Figure 1. Frequency of the most used words in the text codified for the "land degradation causes" objective for Asore (a), Layignaw Arsho (b), Andegna Choroko (c), and the Agricultural Office (d).

In addition, the farmers highlighted several indirect and important drivers in affecting the land degradation. The following indirect drivers were identified: population growth, plot size, land tenure system, land fragmentation. A summary of the main drivers of land degradation identified by the communities is shown in Fig. 2.

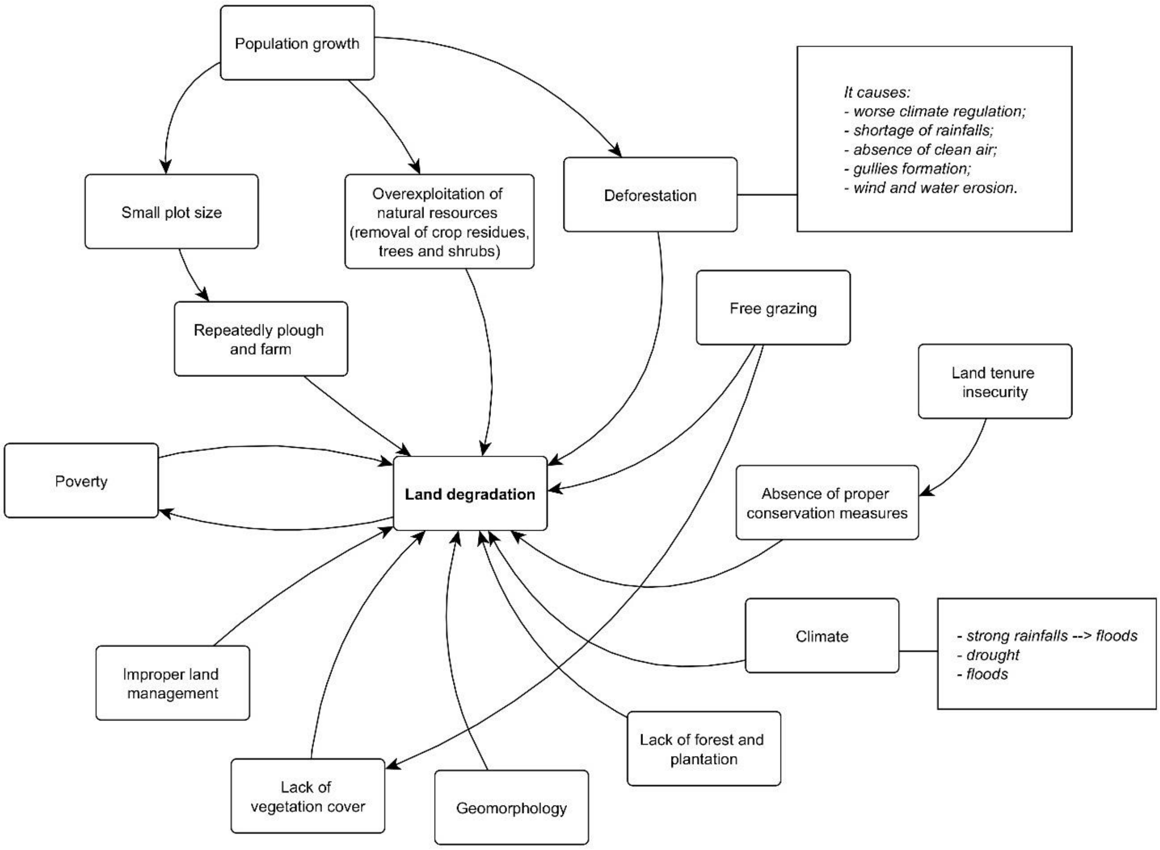

Figure 2. Summary framework to highlight the main drivers of land degradation identified during the participatory approach.

Among the indirect aspects, population growth was identified by the participants as one of the most important in exacerbating land degradation. Accordingly, they recognised the crucial role of population growth in affecting the past deforestation patterns, the declining size of the plot, and the overexploitation of natural resources, as well as introducing land management constraints (such as impossibility of implementing fallow or crop rotation). For further details on population growth and its role in land degradation exacerbation see Section 3.2.

Although deforestation was identified as one of the major direct driver of land degradation by the communities, they asserted that nowadays the deforestation has stopped. Hence, they acknowledged the crucial role of past deforestation patterns in affecting the landscape throughout the past years.

3.1.2. Land management role in land degradation

In this study, the "land management" definition comprehends both the agricultural practices (such as inputs application, intercropping, fallowing, plough), as well as construction of physical structures in the farming land (soil and water conservation measures).

The farmers stated that the soil and water conservation (SWC) measures mostly used in the three *kebeles* are terraces, soil and stone bunds, water diversion against floods, and wind breaks such as rows of trees.

Application of manure and fertiliser, and proper ploughing, were indicated as the most important farming practices used in order to maintain soil fertility and obtain a decent yield. Other important practices for maintaining the soil fertility and enhancing yield were intercropping, crop rotation, fallowing, agroforestry, and planting trees within the plot or in the border of the plot. However, most of these practices were constrained by lack of capacity, by the small size of the plots, and by lack of available labour force.

During the discussions, the communities emphasised some essential factors in determining the effectiveness of SWC measures: constant monitoring and repairing of the structures, proper construction following extension agents' advises and instructions, proper timing to anticipate the rainy seasons, implementation of physical structures together with biological practices (agroforestry), absence of grazing, and absence of wild animals' attacks.

Additionally, the participants also highlighted some drawbacks in SWC measures, such as the inconvenience of cultivate plots were SWC measures (e.g. terraces, stone bunds, and trees' row) are implemented. They also stated that their construction is costly and often difficult.

Even though farmers pointed out that poor and rich households used the same SWC measures, they also asserted that richer farmers could use better construction materials. Furthermore, some farmers pointed out that they started implementing SWC measures after they observed the good effects and outcomes that SWC measures had in other farmers' plots (e.g. enhanced water retention, maintenance of soil fertility, and better yield). Dissemination of knowledge and skills is a key aspect highlighted by the farmers concerning SWC measures adoption.

Richer farmers could apply a better land management because of the availability of oxen to plough in the right time, and the means to buy different inputs (such as fertilisers, pesticide, and improved seeds). Poor farmers, that usually lack of oxen, had to wait and hire the oxen from richer farmers. This aspect, not only determines depletion of the poor households' asset, but it also leads to a delay of the sowing time.

Halaba Agricultural Office's experts highlighted that strong implementation of SWC measures in the area started during the 1985, after a destructive drought followed by a severe famine. Although they noticed that often farmers are not willing to adopt SWC measures because they make plots more difficult to farm, they also asserted that thanks to awareness and extension programs throughout the past years, farmers have become aware of the risk of land degradation, and have started to recognise the importance of SWC measures adoption. The role of the whole community in evoking the adoption of SWC measures was also mentioned. In fact, community often has a strong role in persuading farmers that don't use SWC measures in using good land management to avoid negatively affecting also neighbour farmers. They stated that "*community voice is usually more important and persuasive than government aids and incentives*".

3.1.3. Education role in land degradation

During the discussions, farmers acknowledged the importance of education in land degradation alleviation. Education was recognised as crucial factor in improving land management. Indeed, education facilitates implementation of better land management due to the ability to properly understand developing or extensive agents' instructions. Therefore, the right amount of inputs and proper conservation structures can be adopted.

In addition, education creates more options such as the possibility of getting employed in off-farm jobs, such as trade, carpenter activities, and it increases the ability of practicing dairying, and properly balancing expenditures and managing household asset and savings.

Education of young was also seen as a crucial factor in poverty alleviation. The farmers hoped that educating their children could enable them to get employed in off-farm jobs. However, different constraints were also pointed out. High dropping off rates were identified due to different reasons: lack of capacity, need of labour in the field during harvest and sowing times, lack of job opportunities for young that finished school. Moreover, the latter aspect discourages others younger scholars to further attend their classes.

3.1.4. Land degradation consequences

Several land degradation consequences were identified during the discussions. A reduction of ecosystem services provision (e.g. depletion of spring water quality and quantity, reduction of available thatch grass for constructing the roof of the traditional houses, reduction of fodder grass for feeding the livestock, reduction of firewood and fuelwood) was highlighted by all participants.

Participants also recognised the key role of land degradation in soil fertility depletion. Yet, reduction of soil fertility was seen as a crucial factor in reducing the crop yield exacerbating poverty.

Participants pointed out how land degradation and poverty are strictly connected; poor households rely on natural resources, causing natural resources exploitation and land degradation. Land degradation on the other hand exacerbates poverty by reducing availability of promptly available and valuable livelihoods. They concluded that poverty and land degradation connection represents a vicious circle. They asserted "*land degradation and poverty go hand by hand*".

Moreover, they pointed out other issues linked to land degradation: reduction of land size because of gullies formation and degradation (that subsequently leads to land shortage), few migrations, and livestock's struggle to survive.

Furthermore, gullies were mentioned causing several issues in community social aggregation; farmers stressed that gullies create difficulties in moving within the *kebele*, and also in protecting the livestock from wild animals (i.e. hyena) asserting that "*gullies separate us even if we are near to each other*".

Fig. 3 shows the association level (or correlation) of the word "degradation" with other words in the text of the transcribed interviews and FGDs codified for the "land degradation consequences" objective. The histograms represent the association found in the text for the word "degradation" in the text of Asore (a), Layignaw Arsho (b), and Andegna Choroko (c) *kebeles*. The association function defines the level of correlation among the selected word and the other words in the text. In this case, a correlation limit of 0.4 was chosen, and the ten words that show higher correlation are represented. The word "yield" shows high correlation with the word "degradation" in the texts of all the three *kebeles*, and "poverty" shows high correlation in the text of Asore (Fig. 3a) and Layignaw Arsho (Fig. 3b). In Andegna Choroko's text degradation is correlated to "poverty" with a coefficient of 0.43.

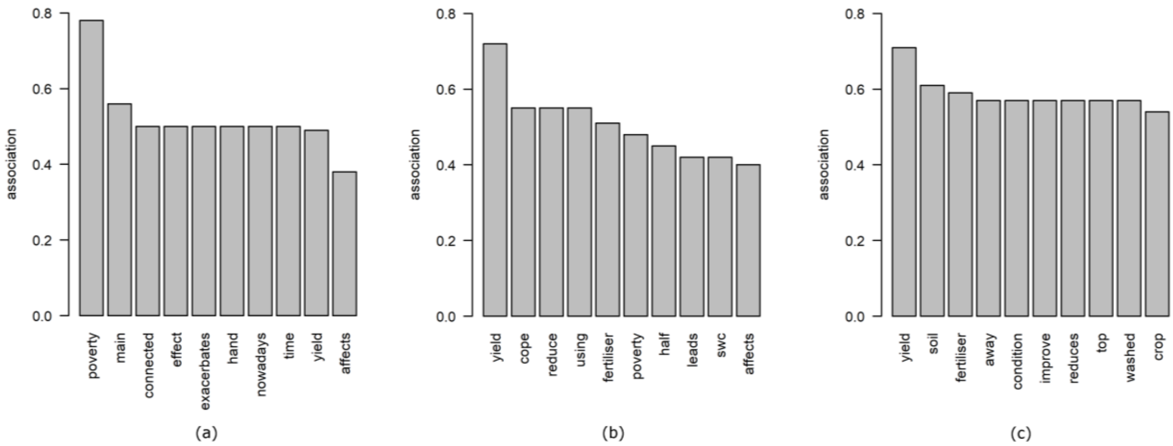

Figure 3. Words correlation with the word "degradation" in the text codified for the "land degradation consequences" objective; Asore (a), Layignaw Arsho (b), and Andegna Choroko (c). To remove and avoid evident correlations, the main stop words and the word "land" were previously removed.

3.2. Population growth aspects

Population growth was mentioned as one of the crucial indirect aspects in affecting the landscape and the land management. Its role in land degradation and poverty exacerbation was pointed out by the farmers in several discussions. This study tried to understand the reason of the increase of population pressure of the last decades, and tried also to infer population growth role in land degradation.

3.2.1. Population growth trends and causes

Firstly, the participants tried to identify the main trends in population pressure of the different recent Ethiopian political periods: i) Haile Selassie imperial regime (until 1974), ii) Derg military regime (from 1974 to 1991), iii) current regime (from 1991 to date). They asserted that the population started growing during the imperial regime and reached higher increasing rates during the Derg regime. They stressed that the population growth is still present in their communities.

Secondly, participants in the three communities mentioned a wide range of factors influencing the population growth. Several causes from very disparate aspects were identified by all the three communities. The political security and the absence of wars were identified as crucial drivers of the current population growth. Furthermore, the increase of health facilities and care centres determined a significant decline in death rate; the health care has notably improved; there is access of medicines, health and nutrition training from the health centres, home support during pregnancy, and deliveries are often arranged in hospitals. Additionally, they highlighted the possibility of getting food aids during shortage of food. They asserted that aids' distribution was not a common mechanism during the previous regimes.

Polygamy was also pointed out by all the three communities as a key factor in increasing population growth. Polygamy leads to higher number of children that subsequently exacerbate poverty. Especially women asserted that lack of awareness regarding the benefits of family planning and the use of various contraceptives is also a leading factor in population pressure increase.

According to the Agricultural Office expert interviewed about the population growth objective, the main reasons of the current increasing trends in population pressure are: polygamy, religious traditions and rules that prevent the use of contraceptives, extensive and widespread dissemination of vaccinations, lack of adoption of family planning, establishment of various health extension programs in rural areas (arguments addressed during the health extension programs are several: sanitation, cleaning and health care, building a secure home, using nets against mosquitos).

3.2.2. Population growth on land degradation

Most of the consequences of population growth adversely affect land degradation. Several aspects link population growth and land degradation. This concept was highlighted by the participants of the three communities, even though different point of views were expressed. Furthermore, the three communities underlined the importance of population growth in decreasing human well-being, and general welfare of the households. The main land degradation consequences directly or indirectly linked to land degradation highlighted during the discussions are reported in Table 6.

Also the Agricultural Office experts highlighted the same issues derived from population growth. The only different aspect highlighted by the experts was about the social gathering and interactions aspect. The experts stressed that with population growth, social interactions positively increase. Community organisations are in fact supported by increase in number of participants, because of the possibility of collecting more money, and therefore increasing the capacity of helping households in need.

The land shortage and the reduction of plot size were two of the more urgent and pressing problems caused by population growth. This concept was incisively stated during one discussion: "*now our children will inherit our small land, but what will the next generation have?*".

Although policy programs have been launched for intensifying the use of contraceptives and the adoption of family planning, the experts of the Halaba Agriculture Office asserted that communities resist to such "new programs" because religious and traditional “rules” are still well eradicated in the communities. However, in Asore, the discussions’ participants asserted that they have started adopting family planning and using contraceptives. This aspect was not pointed out by the other two *kebeles*’ participants. The complexity of the population growth aspect is shown in Fig. 4, that represents the framework of the causes and consequences of population growth identified by the communities.

Table 6. Main consequences of population growth and their effects on the landscape and on the community well-being and welfare.

Population growth consequences	**Effects on environment and natural resources**	**Effects on community**
Deforestation	Higher land degradation (increase of gullies, floods, soil erosion)	Lack of firewood or construction wood.
Vegetation cover depletion	Land degradation increase, reduction of grassland and graze land	Necessity of using crop residues as fuel or for feeding livestock, natural resources exploitation
Large family size	Exploitation of natural resources and fragile and marginal lands	Conflicts for natural resources, reduction of yield per capita, wealth status depletion (reduction of income), conflicts within family because of shortage of land, reduction of land tenure security
Use of crop residues	Croplands more affected by erosion and degradation	-
Expansion of settlement area	Reduction of area suitable for cultivation, natural resources exploitation	-
Reduction of plot size and increase in farmland fragmentation	Erosion for lack of SWC measures adoption, reduction of inputs application	Reduction of crop yield, reduction of household wealth, conflicts within family and among community due to land shortage, subsistence agriculture
Outbreak of diseases	-	Reduction of wealth and health status
Reduction of education	-	Reduction of wealth status, impossibility of sending all the children at school
Reduction of fallow and intercropping practices	Soil fertility depletion	Reduction of yield, food shortage
Social gathering affected	-	Decrease participation in social gathering because of lack of capacity to attend the increasing numbers of weddings or funerals due to population growth.
Livestock reduction	-	Reduction of livestock products as well as livestock labour force, reduction of household’s wealth status

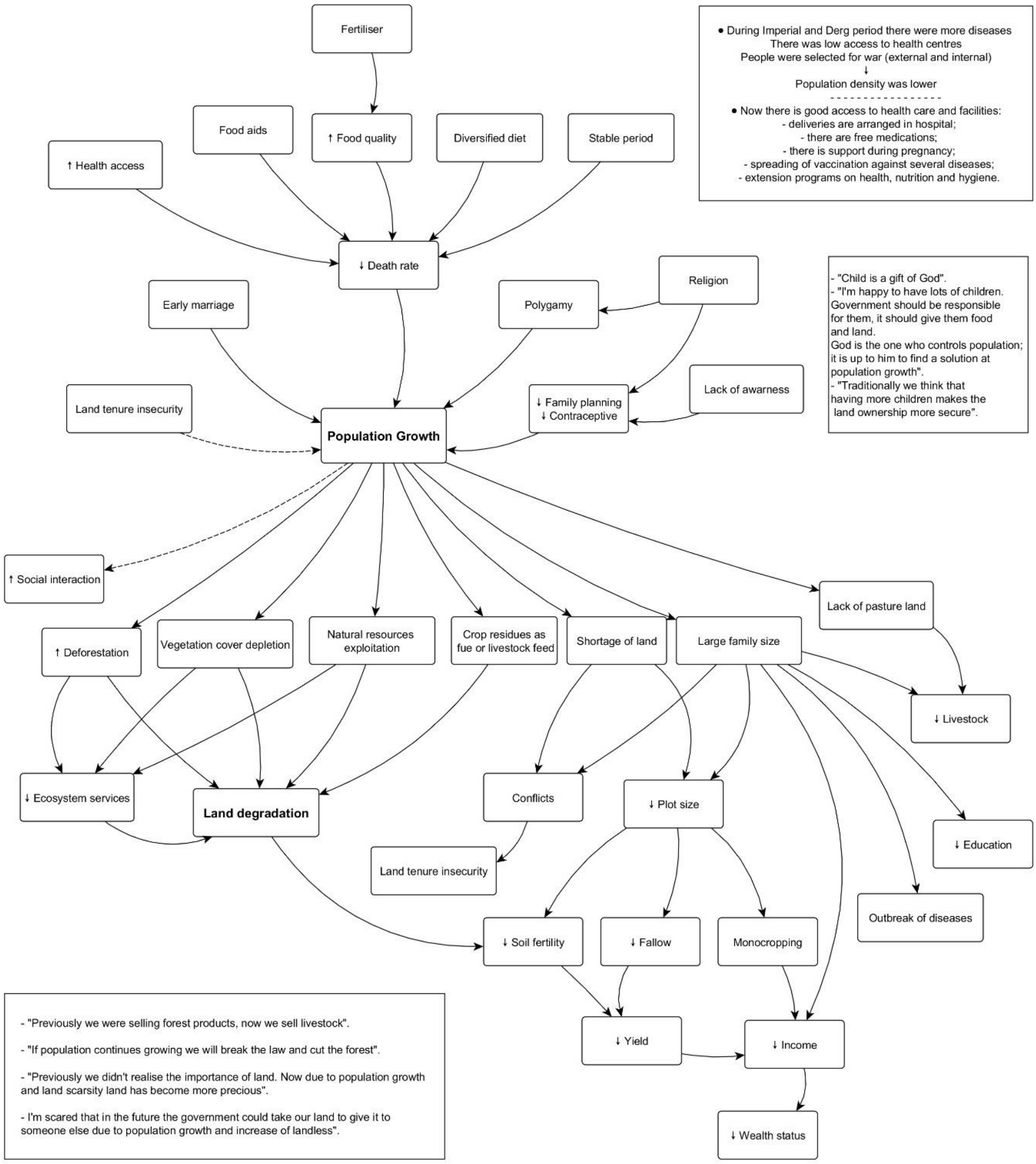

Figure 4. Framework of population growth causes and consequences derived from the analysis of the discussions with the three communities and the Halaba Agricultural Office experts.

3.3. Land tenure system

The three communities highlighted their main property rights on the land as: use, manage and rent rights. They recognised the absence of selling right and they were also not very well informed about renting (exclusion) rights. The expert of the Halaba Agricultural Office clarified the property rights in the *woreda*: farmers (usually male households) hold access, management, withdrawal and exclusion rights, whereas the government holds alienation (selling) right. Due to the absence of alienation right some farmers asserted that they know that the real owner of their land is the government. Yet, even though selling the land property is not allowed, farmers asserted that illegally and informally they could sell their land, based on long renting agreements: "*if the owner dies the rent tenant will keep the land because he won't have back the money payed for the rent; it is a short of illegal, yet uncommon, land selling*".

Most of the farmers got the land during the land redistribution launched after the Derg regime took power in the 1974. In the 1975, the Derg regime announced the land reform with the proclamation "Land to the Tiller". The reform led to land nationalisation though the abolition of previous feudal system, where the landlords held all the property rights and the farmers were tenants that could farm part of the landlord's land and then share the production. Other farmers obtained land through inheritance process. Thus, they asserted that nowadays the only way to get land is to inherit it from the family because of the impossibility of i) getting land from government through redistribution, and ii) buying land from other farmers.

Although the absence of selling (alienation) right was seen as a problem by the communities, the Agricultural Office experts highlighted that the land tenure system assures the well-being of the farmers; in fact, they pointed out that with the alienation right several farmers would sell their land to get easy money and move to the city where they will end up doing begging or getting employed as daily labour without improving their life styles.

An important factor, identified by the three communities, that has improved land tenure right and security was the introduction of the land certificate, in which the borders and the land rights are clearly stated. Most of the farmers got the land certificate within the last 10 years, others didn't receive it yet, but their land has already been measured, therefore they will receive it soon.

3.3.1. Land tenure system role in land degradation

Most of the farmers highlighted the importance of the land certificate to improve their land management and conservation activities. The farmers asserted that now they feel that the land is their own, therefore they apply better management with diversification of crops (with agroforestry practices), as well as introduction of plantation for production of wood. However, they also pointed out that the sense of land tenure security derived from the land certificate makes them using all the resources in their land: "*I started cutting more trees because the certificate gives me every right to cut and use whatever I want from my land*" and "*before I didn't know my rights*". Nonetheless, they asserted that even though they started using more natural resources because of their increasing ownership rights, they also started planting more trees and involving in plantation and afforestation practices.

Generally, the farmers of the three communities agreed that land tenure security is very important for implementation of SWC measures. "*Our land is like the clothes that we wear. If it is our cloth we will take care of it and wash it properly, otherwise we won't*". However, other farmers asserted that they had started implementing better land management before getting the land certificate, hoping that in the future the land would have become "their land". Generally, the participants asserted that the sense of land ownership has greatly improved with the introduction of the land certificate, which is also an important instrument to get inputs (e.g. fertiliser and improved seeds) from the government through half payment base, as well as to secure their land in case of conflicts and claims.

3.4. Other aspects important in land degradation

Other very important factors in affecting land degradation and human well-being were identified by the three communities. In the next paragraphs these aspects are briefly indicated and the main findings reported.

3.4.1. Weather patterns

Different weather aspects were pointed out to highlight their importance in land degradation exacerbation. Intense rainfalls and recurrent droughts were indicated as causes in the increasing water and wind driven soil erosion, respectively.

Patterns of climate change were identified by the communities that in the recent years noticed the following patterns and trends: a reduction of rainfalls amount, erratic and unpredictable rainfalls, shorter and usually later rainy seasons, and longer dry seasons. Concerning the temperature, the three communities mentioned an increase in temperature that has become extremer leading to increase in drought occurrence.

The unpredictability of the weather was pointed out as one of the major constraints in adopting a proper management, due to the difficulty in anticipating the rainy seasons to plan the best periods for sowing or harvesting.

3.4.2. Fertiliser

Fertiliser was mentioned as an important input in order to increase soil fertility, and subsequently improve the crop yield. However, they also pointed out that adding fertiliser in degraded land cannot compensate what has been already lost. "*Fertiliser is useless if the top soil is gone*". Although richer farmers can afford to apply the right amount of fertiliser due to higher capacity, if their land is degraded or if there is flood their management will be negatively affected, regardless their wealth status and their better agricultural practices.

Fertiliser is usually sold by the government through half payment base. Farmers complained about the increasing cost of fertilisers and the impossibility to apply the right amount due to lack of capacity.

3.4.3. Khat cultivation and consumption

Another important factor inferred during the discussions was the role of khat in the land management and household well-being. Khat (*Catha edulis*) is an evergreen plant used as a mild stimulant. The farmers recognised its important social value. Khat is used as gift during weddings, funerals, and to welcome a new-born. Moreover, both male and female participants asserted that chewing khat together increases social interactions and ideas sharing about farming activities. Farmers also pointed out that khat is useful for motivating and stimulating them for hard works in the farmland. Furthermore, khat was considered by participants as a valuable cash crop to increase household income and well-being.

Along with the aforementioned pros, farmers highlighted also several cons linked to khat consumption. Health and behaviour problems caused by intense and continue consumption of khat were mentioned. Moreover, they asserted that khat creates addiction, and often prevents farmers from involving in farming activities. Furthermore, khat consumption is very costly, therefore it reduces household income. Education is also negatively affected by khat, which prevents some scholars from attending school classes.

Accordingly, khat represents a good cash crop if properly farmed and not completely consumed. Therefore, khat could increase household well-being. Yet, the majority of the farmers stated that the negative effects and cons of khat consumption outweigh the positive aspects. Overall farmers asserted that khat consumption exacerbate poverty.

3.4.4. Market access

During the discussions, the role of market access in land management quality and general well-being was also addressed.

Market proximity and access were mentioned as important factors for having a better land management. In fact, they give the possibility of i) buying agricultural inputs and tools, ii) employing daily labourers, iii) spending less money for transportation to buy agricultural materials, and iv) engaging in trade or other business activities. Moreover, market access enables selling crop production (surplus), to increase household asset, hence facilitating livelihoods diversification.

On the other hand, contrasting point of views were also shared during the discussions. For example, Layignaw Arsho community asserted that the market in their *kebele* is too small to purchase agricultural inputs. Moreover, always in Layignaw Arsho, participants highlighted that the market proximity leads to waste time in the market and spend time chewing khat, instead of working in the plot and keeping the livestock far from the plot. In Asore, some farmers (i.e. poor female FGD) stressed that the proximity to the market could lead to incapacity of managing money properly and the risk of spending money in not necessary items. Furthermore, they also asserted that having better access to the market could influence and make them to sell their land. They stressed that this aspect could then decrease their livelihoods and lead to poverty exacerbation.

3.5. Resilience to land degradation

For resilience, this study meant, as defined by Adger (2000), “the ability of groups or communities to cope with external stresses and disturbances as a result of social, political, and environmental change”.

By contrast, vulnerability can be defined as the sensitivity and susceptibility to get harmed from the exposure to stresses due to social and environmental changes and from the absence of adaptation capacity (Adger 2006; Gallopín 2006).

Determinants of resilience and vulnerability to land degradation were also inferred during the discussions. According the three communities, the vulnerability and the resilience to land degradation is determined by:

- Capacity/Savings: possibility to apply right amount of inputs, to implement a better land management, and to cope with harsh periods by using the savings;
- Attitude: farmers that spend time in properly managing their plot can cope with and be resilient to land degradation;
- Education: good knowledge on how properly construct SWC measures and on the proper amount of inputs application help enhancing the yield;
- Farming type: intercropping helps in adapting to land degradation and climate change;
- Farmland type: plot size, and plot location (those farmers with small plot or plot located in steep area or in area exposed to flood are more vulnerable to land degradation regardless their wealth status);
- Involving in PSNP (Public Safety Net Programs): in order to get aids;
- Diversification of activities: involving in trade or as daily labourer;
- Household size: high number of children leads to higher vulnerability to land degradation.

Although communities stressed that generally richer households can better cope with land degradation, they also underlined that everyone is vulnerable and nobody is resilient to intense land degradation and recurrent droughts. However, they also asserted, that despite the fact that land degradation affects the whole community, "*rich households are more resilient at the beginning because they can rely on saving and on better income, and they can involve in other activities as trade*".

The importance of the wealth status in affecting the resilience to land degradation highlighted by the communities during the interviews and FGDs can also be identified from the word clouds in Fig. 5, that show the most used words in the text codified to represent communities' thoughts and perceptions about the factors that matter in land degradation resiliency. The frequency of the words is defined by the colour (from black to light grey), the size (from big to small), and the position (from the centre to the borders). The word clouds are divided by gender, male (a) and women (b). As it is shown in the word clouds, some of the most used words are "poor", "rich", "wealth", "capacity" and "poverty".

Although this approach can identify major trends on the text, a careful qualitative analysis was important to identify other aforementioned patterns. However, throughout the word clouds it is possible to underline the major aspects identified by the communities to infer land degradation resiliency: the wealth status and the capacity of each household.

(a) (b)

Figure 5. Word clouds of the words mostly used in the text codified for the land degradation resiliency topic. The words' colours (from darker to lighter) and the sizes (from bigger to smaller) define the frequency of the words in the text. The texts of the interviews have been divided by gender: male (a) and female (b).

3.6. Coping strategies

One of the several aims of this study was also to identify the coping strategies adopted by the communities against land degradation, climate change, and to assess possible solutions for reducing land degradation and poverty. In the following paragraphs, the coping strategies against land degradation and the possible solutions to land degradation mentioned by the three communities are reported.

Among farming strategies indicated as coping strategies, the three communities mentioned i) the strategies of cultivation coffee and khat (cash crops) for increasing the income, and ii) involving in afforestation in private plot. In order to tackle land degradation, they asserted that good practices would be: higher implementation of SWC measures, use of better land management and proper amount of inputs, fencing plots and planting Eucalyptus, engaging in home gardening and vegetable farming. If the land degradation is too intense or the weather conditions are too severe (e.g. intense droughts and floods) they mentioned that good coping strategies are: engaging in trading (petty trade), selling livestock, engaging in sand extraction, migrating and working as daily labourer. Engaging and involving in PSNP (Public Safety Net Programs) was also reported as an important coping strategy to escape the severe land degradation impacts.

Other participants asserted that they don't adopt any coping strategies, they simply wait for government helps and aids, or they pray Allah. The absence of strategies was mainly found regarding the severe effects of the climate change. Although migration was mentioned as possible solution to cope with land degradation and climate change, most of the participants considered migration as the last option; "*we have children, where could we go?*". Migration was seen as an opportunity for young of the *kebeles*, especially female young, that could get employed as maid in Arabic and other Muslim countries (Sudan, Saudi Arabia, United Arab Emirates) and help the family by sending back money as remittances.

3.7. Scenarios development

In the scenarios development almost all the participants highlighted the importance of population growth in exacerbating land degradation. In Fig. 6 some of the scenarios drew by the farmers are shown.

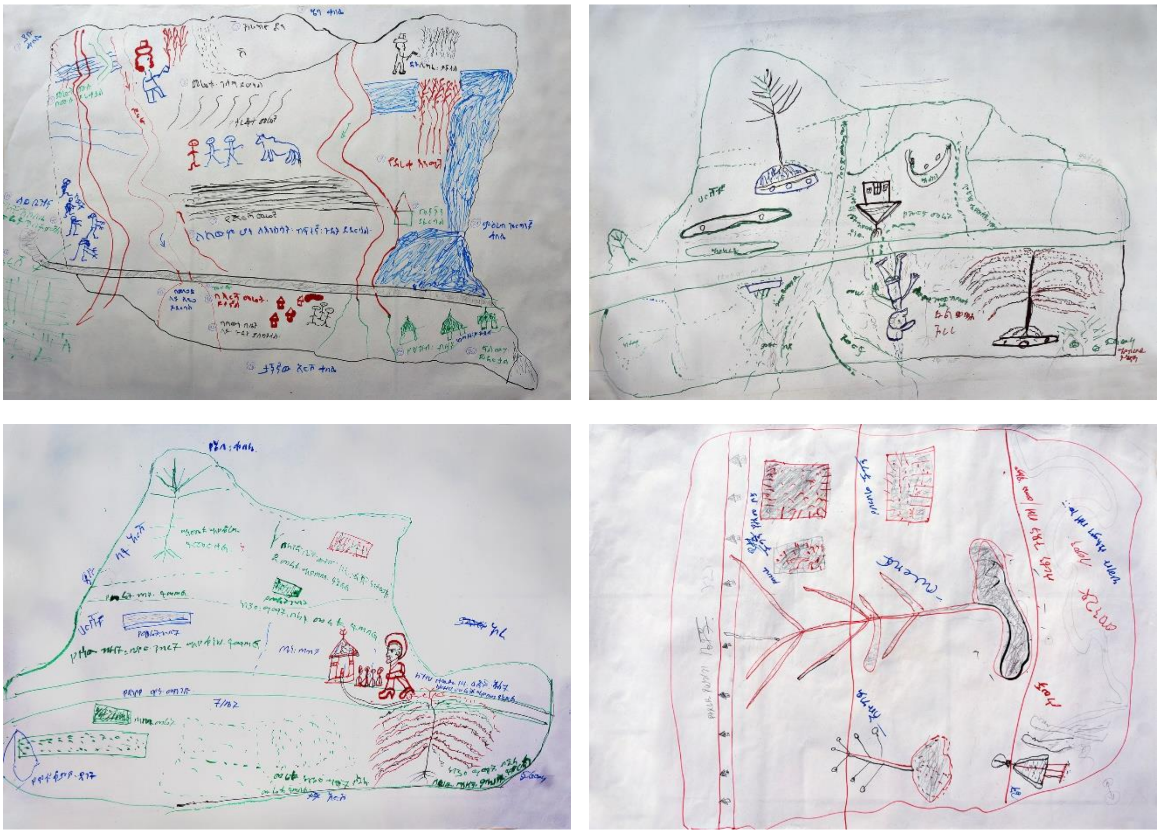

Figure 6. Drawings made by the participants during the FGDs on scenarios development. On the top left the scenario A drew by the male participants of Layignaw Arsho, on the top right the scenario B drew by the female participants of Layignaw Arsho, on the down left the scenario C drew by the female participants of Layignaw Arsho, on the downright the scenario D drew by the male participants of Asore.

Among land management, population growth and climate change, population growth was often indicated as the major cause of land degradation, and also as the major constraint in adopting better land management. On the contrary, the Agricultural Office experts asserted that population pressure can be controlled through the recent introduction of family planning programs, while the climate change cannot be stopped. They asserted that if the past trends of climate change continue the livelihoods and well-being in the *woreda* will be jeopardised and the poverty will increase.

Farmers asserted that with better land management they could counteract the damages of the climate change, but with the increase in population pressure, and the scarce availability of farmland, the overexploitation of natural resources will enhance leading to an overall increase of land degradation, with reduction of well-being regardless the wealth status.

Fig. 6 shows some of the scenarios paintings drew by the communities of the four *kebeles*. Male participants of Layignaw Arsho (top left image, scenario A) depicted some gullies formation and high natural resources exploitation due to population pressure. In the drawings some of the impacts of strong flooding events are shown. In the top right image, the female participants of Layignaw Arsho depicted a man and a house carried out by the water, together with the destruction of some conservation measure structures (scenario B). On the contrary, in scenario C, female participants of Layignaw Arsho forecasted a better land management that led to better landscape and well-being in the down left image (scenario C). The male participants of Asore delineated an environment characterised by high implementation of restoration measures in scenario D (image on the down right).

For further details on the results of the scenario development FGDs refer to Chapter 5.

4. DISCUSSION

4.1. Participatory approach limitations

Although participatory approach methods represent effective means to gain a holistic and broad knowhow of the local system and of the forces in work, it can also have some drawbacks. In fact, participatory approach methods are often time consuming (Chambers 1994a; Chambers 1994b; Cornwall and Jewkes 1995; Luyet et al. 2012), they requires several skilled facilitators (those who conduct the discussion and facilitate the ideas sharing) (Chambers 1994a; Reed 2008) depending on the language spoken by the community, and they could be bias by the presence during the discussion of powerful people (such as people involved in policy, or people that work for the government, as well as man or other powerful groups). Carrying out a total of 32 interviews and 33 focus group discussions proved to be time consuming and challenging especially for finding the proper number of participants.

The work was also challenging because of the necessity of changing facilitator for translating from Amharic to English. Hence, different facilitators' backgrounds could have influenced the participants' answers by addressing the discussion into the field of expertise of each facilitator.

Another aspect that could have affected the interviews and the discussions was the participation at the discussions of the local development and extension agents. This could have led the farmers not to be completely sincere in all the issues, especially about issues that involve the government. The presence and participation of local facilitators was however necessary because of the impossibility of conducting the discussion in Amharic since most of the participants were not able to properly express themselves in Amharic, but they could only speak the Halaba local language.

Furthermore, a criticism of using a local participatory approach is to mainly focus on local micro-level dynamics and causes, hence ignoring broader and more systemic and macro-level causes and structures, which might be decisive also at local level. Even though this study included larger scale factors (e.g. historic and political changes), other important factors might have been remained invisible (e.g. Ethiopian policies on foreign investments and development projects, on markets and international treaties and organisations that overall could affect crops and inputs' prices, migrating options, as well as economic incentives). While these larger scale and macro-level aspects have often an influence at a local level on possible choices, options and constraints faced by the communities, they might be difficult to uncover through a local level participatory approach (Mohan and Stokke 2000; Midgley and Garred 2013).

Finally, the Agricultural Office experts asserted that usually farmer try to picture a worse situation that it really is, because they hope to get aids from NGOs or from the government. Therefore, they asserted that farmers always exacerbate the problems for gaining more attentions from different organisations. As pointed out by Narayan et al. (1999), especially in poor countries, poor people hope to be heard and they hope to obtain some helps from outsiders. This aspect must be recognised in order to avoid raising expectations and hopes that cannot be met by the participatory approach (Cornwall and Jewkes 1995).

4.2. Participatory approach to address land degradation issue

Participatory approach constitutes an effective method to gain local perspective, achieve comprehensive understanding, and give voice to rural and poor communities (Cornwall and Jewkes 1995; Reed 2008; Raymond et al. 2010; Luyet et al. 2012; Whitfield and Reed 2012). When trying to infer land degradation risk, it is necessary to address the main issues from the point of views of the communities that rely on the natural resources affected by land degradation.

In this study, through a comprehensive participatory approach, local perspective on social, economic, and cultural as well as biophysical aspects was addressed. This was also related to how the several aspects identified affect community well-being (Whitfield and Reed 2012). In fact, the study tried to address land degradation causes and consequences with the aim of achieving a better knowledge on how the several drivers identified from the participants affect their livelihood and well-being, and how they are related to poverty alleviation or exacerbation. Local knowledge and experience are very important when trying to inform and support decision-making processes in order to promote development strategies and sustainable management of natural resources (Reed 2008; Cundill and Fabricius 2009; Hage et al. 2010; Leys and Vanclay 2011; Luyet et al. 2012).

The several discussions and interviews emphasised the high complexity of the land degradation risk in poor rural communities in the Ethiopian landscape.

The participants often indicated lack of awareness as major constraint in adopting sustainable management for reducing the occurrence of land degradation. However, they asserted that in the last years, education from the Farmers Training Centre (FTC) has become an important aspect, and knowledge sharing among farmers has also improved and facilitated the adoption of better land management. Since few years, they started recognising the importance of SWC measures implementation. Conservation measures adoption was also indicated as a priority because of the land shortage; a farmer stressed that "*Now that there is no other land available, we really understood the importance of taking good care of that land. Now land is more precious because is scarcer that before*". This could be determined by the U-shaped relationship between population pressure and soil conservation or collective sustainable land management, and soil erosion: with the increase in population pressure the land management improves due to land scarcity, knowledge exchange with development of alternative technologies and practices, awareness development, as well as increase in labour force. Consequently, better land management leads to reduction of soil erosion.(Tiffen et al. 1994; Templeton and Scherr 1999; Gebremedhin et al. 2004; Koning and Smaling 2005). Yet, participants indicated that depending on the wealth status, farmers where using different materials, with richer farmers that were able to construct more effective structures because of the possibility of purchasing better materials.

However, farmers also indicated some drawbacks and side-effects in SWC measures implementation. In fact, they make more difficult to cultivate (ploughing), they reduce the available land for cultivation, their construction is time consuming, and they also represent suitable habitats for weeds and animals that could damage the harvest (such as rodents and concerning afforestation practices also warthogs, monkeys, or porcupines). This latest aspect was indicated as one of the problem of conservation measures adoption also by other Ethiopian studies (Shiferaw and Holden 1998; Shiferaw and Holden 1999; Hengsdijk et al. 2005; Kassa et al. 2009; Tefera and Sterk 2010; Byg et al. 2017), that although reported also several benefits which generally overcome the harmful drawbacks (Shiferaw and Holden 1998; Gebremichael et al. 2005; Byg et al. 2017).

When highlighted this problem to the Agricultural Office experts, they asserted that a good practice against animals' attacks is to cultivate crops that are less affected by animals (such as teff or chilli pepper). However, Shiferaw and Holden (2000) indicated teff as one of the cultivation that leads to higher rate of erosion and nutrient depletion. Moreover, the suggested practice showed that the Agricultural Office probably does not often take into account people's realities for solving pressing problem. In fact, teff and chilli pepper are mainly cash crops that only households with large amounts of land or better income could afford to grow, whereas the priority of the majority of the households is to cultivate subsistence crops for fulfilling their basic needs (e.g. maize).

Considering the benefits of exclosure areas, farmers but especially Halaba Agricultural Office experts, also highlighted the increase of water retention due to several water harvesting structures, that however determined the increase of suitable habitats for different insects, among them also mosquitos responsible of malaria disease outbreaks. This aspect, coupled with the harmful damages caused by wild animals such as warthogs or monkey that found in exclusures suitable habitats, were indicated as major drawbacks of exclosure areas. Similar findings were found by Byg et al. (2017). However, no measures have been studied for alleviating the dis-benefits faced by the farmers that own land close to the restoration areas. No compensation measures were pointed out by participants, and the prohibition of hunting wild animals was exacerbating the dissatisfaction and malcontent on exclosure areas' establishment. This aspect was mainly found in Asore *kebele*, even though participants recognised the benefits brought by exclosure areas' establishment (e.g. soil recovery, soil erosion reduction, microclimate regulation).

Furthermore, the farmers indicated that an important factor in affecting the effectiveness of SWC measures is the climate change. In fact, they stressed that many structures have been destroyed by intense rainfalls and by severe floods that occurred in the last decades and especially in the spring 2016.

Therefore, considering other studies findings and the opinions of the farmers interviewed for this study, soil and water conservation measures and restoration practices, such afforestation or exclosure, constitute important measures for reducing land degradation. There is yet the need to acknowledge the presence of dis-benefits in adopting SWC measures and in the establishment of exclosure areas (such as labour constraints, capacity constraints, time needed for constructing proper conservation structures, pest and diseases spreading) that might contribute to their scarce utilisation and community dissatisfaction. Tadesse (2001) found that many exclosures were destroyed during the government change in 1991, and pointed out that the establishment of private ownership right of exclosure areas to individual farmers would improve their conservation and sustainable use. Thus, compensation measures should be considered in order to repay the damages caused by wild animals (Kassa et al. 2009), and/or floods and intense climatic events. Furthermore, other important mechanisms that could be introduced, in order to enhance sustainable management, are the payments for ecosystem services. In fact, the farmers, since they are often susceptible to food insecurity, could fail to see the importance of adopting conservation and restoration measures (e.g. afforestation practices), if they don't bring short-term benefits (MEA 2005).

Compensation and payment for non-marketed ecosystem services (such as carbon sequestration and soil retention) are mechanisms that could represent, in the future, important tools to reduce land degradation, as well as alleviate poverty (MEA 2005; Engel et al. 2008; Bulte et al. 2008; Antle and Stoorvogel 2009). A market-based approach that acknowledges non-economic and non-marketed ESS benefits (e.g. climatic regulation, soil fertility, sediment retention) is fundamental to tackle land degradation (MEA 2005) especially in developing countries where people are strictly dependent on natural resources. This is the case of the study area in Halaba *woreda* where households could be highly affected by reduction of promptly available livelihoods, due to SWC measures and afforestation practices implementation, in a short-term scale. However, the Payment for Ecosystem Services (PES) schemes need to consider the risk that farmers could face in investing in uncertain off-set or carbon credits. Yet, the promised "output" (e.g. soil carbon savings) of the PES scheme could be frustrated and jeopardised by flooding and drought, affecting farmers' willingness to buy carbon credits from PES schemes projects.

Furthermore, participants stressed that one of the main constraint in using better land management is the population growth. They asserted that due to population pressure the plot size have been reduced, and the amount of food production needed has increased, hence they cannot implement SWC measures, or afforestation practices, because they need to cultivate the whole available land. Other farmers asserted that the only aspect that matter in SWC measures implementation is the awareness of the benefits derived by better land management, and the attitude of working hard for improving their well-being. Thus, participants agreed that better land management helps increasing the yield, because of better soil fertility and water retention. In a participatory study, new techniques and farming technologies were tested with the distribution of aid incentives to make subsistence farmers willing to try new farming methods without fearing of losing their basic needs (Liu et al. 2008). This could be the strategies to adopt in order to spread the adoption of new technologies and practices by farmers that are usually unwilling to change their traditional farming practices because of the fear of losing part of their production that constitutes their basic livelihoods. These type of participatory watershed development programs (Liu et al. 2008) can be used as farmers' training and are important for showing farmers alternative production methods that will enhance their livelihoods. Furthermore, successful programs are likely to be adopted also by other farmers that recognise improvements obtained by neighbour farmers in their farmland and in their well-being status. For example, in the study area, diversification of livelihoods through agroforestry and diversification of crops should be incentivised. There is, however, the need to guarantee better market access; this will enable farmers to sell their crop yield surplus. Improper market access constituted a constraint for the economic development of the *kebeles*, apart from Andegna Choroko that benefits from its vicinity to Halaba city. In fact, scarce transportation infrastructures and poor access to the markets affected land use and management patterns, technologies adoption, farming type choices (subsistence or intensive), income and development (Scherr and Yadav 1996; Barbier 1997; Desta et al. 2000; Tefera et al. 2002; Hagos et al. 2002). Therefore, in order to adopt better land management, there is the need to solve the problem of resources constraints by achieving inclusive economic growth, that it is possible only considering several factors, from environmental to socio-economic and political aspects.

Even though several opinions were shared, the majority of participants agreed that population pressure has to be reduced in order to reverse and stop land degradation trends. These findings agreed with other Ethiopian studies that indicated the population pressure as the major indirect cause of land degradation (Hurni 1988; Hurni 1993; Taddese 2001; Biazin and Sterk 2013).

Population growth was also indicated as possible constraint in land tenure security. Several farmers, in fact, asserted that if the population continues growing they are scared that the government will redistribute the land because the landless will increase; therefore, they are scared of losing their land in the future. High population pressure was also seen as possible source of conflicts among community, as well as within the family because of the land scarcity. This possible outcome was already found in other area of Ethiopia, where high population growth, and farmland shortage as a result of urban expansion, led to conflicts, migrations and also increasing number of jobless and addicted people that affected security and peace of rural communities (Bogale et al. 2006; Haregeweyn et al. 2012).

However, the farmers were generally happy about the current land tenure system. The land certificate, which most of the households already received, was perceived as an important instrument for securing their property rights. Thus, despite several studies indicated that land tenure system in Ethiopia is a constraint for better land management (Bogale et al. 2006; Tefera and Sterk 2010), this was not the case of Halaba *woreda*. The introduction of the land certificate was important for enhancing farmers' willingness to adopt better land management, because of stronger feeling of ownership as compared to the past years.

In comparison to the past, the farmers were more aware of their rights. However, renting processes were often obscure to the farmers. Moreover, some farmers were not happy of not having selling right (alienation right) and they felt their land was less secured because the government hold alienation right. Another aspect highlighted by the farmers was that nowadays the only way to obtain land is through the land inheritance process. Now that the land has become scares, this system could lead to an increase of landless. Farmers with small farmland usually were renting in (with sharecrop strategies) farmland of older farmers that lacked of labour force. Poor land management was usually reported in sharecropped fields, as indicated also by Tefera and Sterk (2010).

Despite households' awareness about the harmful impacts of population growth and although they recognised the importance of family planning, few farmers have started adopting it. The tradition and religious "rules" are, in fact, much eradicated in the communities. A male farmer of Andegna Choroko *kebele* well represented community thinking and reason: "*Children are gifts of God; the government should take care of them. We are happy to have many children*". On the contrary, especially in Asore, both male and female FGDs participants stressed that, in their *kebele*, households have started adopting contraceptives and family planning in order to reduce family size and increase overall well-being. Therefore, extension programs have been already carried out for teaching households to adopt family planning. However, there is the need to work more on this aspect to reverse traditional thinking for achieving comprehensive and inclusive social development. Another aspect that could contribute to the population growth is the lack of proper and inclusive social security measures (e.g. pension schemes, injury and disability insurances, unemployment payments) (A. Byg, personal communication). Hence, having many children is a short of social security strategy for the parents to ensure they will be provided for in old age. Accordingly, some studies found that the introduction of proper social security system and schemes could foster a reduction on population growth trends, as well as promote economic development and growth (Hohm 1975; Zhang and Zhang 1995).

Considering the resilience to land degradation, it appeared clear that the participants, although asserting that everybody was highly affected by land degradation, believed that wealth status was a key aspect. Richer farmer can use income for coping with harsh period, they can construct better SWC measures because of possibility of purchasing better materials, and they can also manage better their land thanks to oxen ownership. But, the participants asserted that all the households are indiscriminately affected by land degradation, regardless their wealth status. "*Richer household are more resilient at the beginning; richer became poorer, poorer became much poorer, but at the end everybody is affected in the same way by land degradation*". However, richer farmers can use better material for SWC measures, apply the right amount of inputs (especially fertiliser), and plough on time thanks to oxen availability and ownership. This make them more resilient, however if the land degradation continues at the current rates nobody will be safe and there will be a reduction of well-being in the whole *woreda*. However, Byg et al. (2017) found that poor households had less access to exclosures benefits (such as timber and grasses for thatch and fodder) compared to rich households that could even break the law (e.g. by obtained larger amount than the allowed quota, or by stealing timber without being frightened of being caught due to the possibility of affording the fines imposed) in order to gain more benefits from exclosure areas. Therefore, although participants asserted that everybody is affected indistinctly by land degradation, it was clear from the different discussions that wealth status definitely affects household resilience.

Finally, the participants did not report strong coping strategies and mechanisms against land degradation and climate change impacts. From the several FGDs appeared that their reliance to government aids was particularly strong; this was likely determined by the harsh period (intense drought) that affected the study area in the year before the participatory approach was carried out (year 2015), and that continued during the participatory approach execution with recurrent floods (year 2016). It was found that in Asore the households were lacking of coping strategies both concerning livelihoods diversification and engagement in alternative activities (apart from farming). In Andegna Choroko, on the contrary, participants showed higher adaptability to droughts or harvest failures. This was not surprisingly considering the vicinity of Andegna Choroko to the city Halaba. The city vicinity guarantees better market access, possibility of engaging as daily labour or in petty trade, and it likely supports better knowledge exchange and social inclusiveness.

Some farmers asserted that a good coping strategy for the future would be to educate their children; they hope that education will enable their children to get employed in off-farm activities. However, this aspect could be constrained by the land tenure system that does not permit to sell the land. As mentioned by the experts of the Halaba Agricultural Office, the lack of selling rights on the land prevents farmers to move to the cities. Although they mentioned that this is a good measure to avoid over-migration and begging style of life of landless in bigger cities, it is also a constraint for achieving development and growth through the generation of higher options and opportunities for educated young. In fact, the lack of off-farm job opportunities in the study area could force young to move to other cities for finding job opportunities. Yet, lack of capacity and the absence of proper land market likely constraint the generation of off-farm opportunities generation as well as scholars' willingness to pursue higher education level. During a male FGD in Asore, participants also asserted that they hope that their children, thanks to education, will change their attitude and will marry just one wife, and therefore will have fewer children. Education was found to be also very important for using proper land management, and for adopting soil and water conservation measures. This concur with other studies that stressed that education plays a key role in improving productivity, and promoting efficient use of resources and sustainable agricultural management (Bishaw 2001; Bogale et al. 2006).

Despite the intense land degradation that can be observed in the study area, in the past years several steps forward have been achieved (e.g. implementation of exclosure areas, better land tenure system, development of extension programs, better health care system), but with the increase of climate change impacts and the increment of the population pressure, more should be done for reversing land degradation and ensuring well-being development and poverty alleviation. This study showed that appraisal of the complexity of land degradation risk can be achieved through participatory approach programs. Besides, strong participation of rural communities in decision-making processes and strategies is key for developing sustainable agricultural management strategies (Scherr and Yadav 1996; Shiferaw and Holden 1999; Tekle 1999; Liu et al. 2008).

Due to the complexity of the system, for achieving inclusive and comprehensive development and sustainable growth, decision-making programs must acknowledge the importance of several and different aspects, such as conservation and restoration activities, education development, family planning programs, job opportunities diversification, market access, and transportation infrastructures development. As Hurni (1988) stressed, natural resources' restoration and conservation, although a crucial issue, won't be enough for achieving a sustainable development; therefore Ethiopian communities will have to undergo massive change to improve their life and well-being and to alleviate poverty. However, it is unlikely that the three *kebeles*' communities will be able to achieve sustainable development and to alleviate poverty by themselves. The vicious circle between poverty and land degradation that was pointed out by this study constitutes a wicked problem that requires proper interventions that consider several aspects (e.g. land management, land tenure system, market access and development). Furthermore, when trying to achieve inclusive development and growth strategies there is the need to address trade-offs between short-term needs (such as food production and generation of minimum level of income), and longer-term sustainability. These intractable and wicked problems are extremely difficult to address and require interventions at local level as well as at national and international level.

5. CONCLUSIONS

This study showed that participatory approach represents an effective means when trying to infer land degradation risk in rural communities of developing countries. The local knowledge and perspective proved to be important in order to assess complex issues, such as land degradation risk, in complex system as Ethiopia society, where several factors are involved. Comprehensive and inclusive development and restoration strategies and programs can be planned just if the voices of the communities involved in the overexploitation of the natural resources are listened and considered. Interdisciplinary studies are necessary when different aspects, such as socio-economic, political as well as biophysical factors are to be targeted in order to trigger economic and sustainable development.

Therefore, to inform decision-making processes, extensive participatory approach programs could be coupled with other scientific or quantitative data for achieving comprehensive and accurate assessments, where local communities are the focus of the attention. This approach could help in shaping and exchanging knowledges and experiences that are key factors for a sustainable development.

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CHAPTER 5

Spatial Bayesian Belief Networks for mapping land degradation risk[3]

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Authors: Stefania Cerretelli[*,a,b,c], Laura Poggio[a], Alessandro Gimona[a], Tewodros Tefera[d], Yiteg Alemu[d], Markos Budusa[d], Thomas Lemma[a], Yitna Tesfaye[d], Paula Novo[e], Anja Byg[a], Getahun Yakob[f], Shiferaw Boke[f], Mulugeta Habte[f], Malcolm Coull[a], Alessandro Peressotti[b], Helaina Black[a]

* Corresponding author, [a] The James Hutton Institute (United Kingdom), [b] University of Udine (Italy), [c] University of Trieste (Italy), [d] Hawassa University (Ethiopia), [e] Scotland's Rural College (United Kingdom), [f] Southern Agricultural Research Institute (Ethiopia)

1. INTRODUCTION

Land degradation represents a natural, as well as human-induced phenomenon, which encompass and comprehend different aspects. It is caused by a combination of socio-economic and biophysical factors. Therefore, integrating different sources of information, with an interdisciplinary as well as transdisciplinary approach, it is fundamental for assessing land degradation risk, and for obtaining accurate and significant appraisals that can be used in decision-making processes. Bayesian Belief Network (BBN) represents a good tool to integrate different sources of knowledge and information (e.g. local and expert knowledge, GIS modelling), and to look at different factors and their relations and dependencies.

1.1. Bayesian Belief Network modelling for environment assessments

In order to restore degraded land or to preserve areas subjected to land degradation, there is the need to map and quantify land degradation. Bayesian Belief Network (BBN) is a tool that can be used to consider different aspects from several disciplines (such as social, economic, environmental, and biophysical aspects).

BBNs are probabilistic graphical models that consist of a set of variables (nodes), and their conditional dependencies and independencies (represented by a set of directed edges or arcs of arrows), in a form of a directed acyclic graph (DAG). The directed edges define parent nodes and children nodes; feedback arrows between parent and children nodes and closed loop links are not permitted (i.e. children node cannot influence parent nodes, and a node cannot influence itself). Each variable (node) is characterised by a set of mutually exclusive states. The strength of the probabilistic relationships among the different variables and their states is defined by a conditional probability table (CPT) (Jensen and Nielsen 2007; Gonzalez-Redin et al. 2016). CPT defines for each child node state the probability of it occurring given all possible combinations of the parent nodes' states (Gonzalez-Redin et al. 2016).

BBN modelling supports the study of environmental systems, where different variables can be taken into account (Marcot et al. 2006; Aalders 2008; Aguilera et al. 2011; Gonzalez-Redin et al. 2016). BBN represents a good tool to look at different system's factors and to handle qualitative and quantitative variables. Therefore, BBN modelling is a useful tool for integrating participatory and qualitative information with quantitative and spatial data, and knowledge from different domains such as field data, modelling results, as well as experts and stakeholders knowledge (Aalders 2008; Pollino and Henderson 2010; Gonzalez-Redin et al. 2016). Furthermore, the BBN ability to account for uncertainties and their propagation, and to manage missing values in the input data, makes BBN tools very useful to study socio-environmental systems (Uusitalo 2007; Pollino and Henderson 2010; Aguilera et al. 2011; Landuyt et al. 2013; Celio et al. 2014; Phan et al. 2016).

The integration of GIS layers in the BBN modelling enables to derive spatially explicit BBN outcomes. Several studies integrated GIS and BBN for mapping and assessing several environmental impacts and aspects (Smith et al. 2007; Aalders 2008; Aitkenhead and Aalders 2009; McCloskey et al. 2011; Verweij et al. 2014; Celio et al. 2014; Gonzalez-Redin et al. 2016). Despite these promising aspects, Aguilera et al. (2011) found that the use of BBN modelling is still scarce in environmental science.

BBN modelling could facilitate decision-making processes by making the information more accessible and visually immediate (Gonzalez-Redin et al. 2016). In fact, the BBN modelling represents a multi-criteria analysis useful to describe and subsequently adopt a potential win-win situation in order to address a sustainable use of the ecosystems (Gonzalez-Redin et al. 2016).

This study aimed to map land degradation risk using the probabilities derived from a BBN. Several scenarios were developed to identify population pressure and conservation measures role in affecting land degradation. This assessment is relevant because of the high rate of soil degradation that affects the study area. Mapping the probability of increase of land degradation represents a useful approach to target areas for reducing land degradation.

In this study, ecosystem services modelling results were integrated with other information (from literature review and participatory approach), using BBN modelling. This method generated a synthetic scenario assessment on land degradation risk that could represent a good means to explore possible policy interventions and to facilitate access to complex information, making it more accessible and readable. Moreover, the derived probability maps represent a good means to prioritise certain conservation strategies and target degraded areas.

The main aims of this study were to i) highlight trends of land degradation in different scenarios to address changes in population pressure, conservation measure implementation and land management, using bio-physical models and information gathered via stakeholders' elicitation, ii) identify possible target areas for restoration measures implementation, and iii) suggest interventions to help reducing land degradation.

2. DATASETS

2.1. Land use information

The land use classification was derived from the supervised classification described in Chapter 2 and 3.

The conservation measures identified using Google Earth® images as background (see Appendix A) were also included in the land use dataset previously created. Ten land use classes were identified. Fig. 1 shows the derived land use map and Table 1 shows the land use classes' description.

See Chapter 2, Chapter 3, and Appendix A for further details on the land use classification, and Appendix A for details on conservation measures identification, that were used for the P factor of the RUSLE equation.

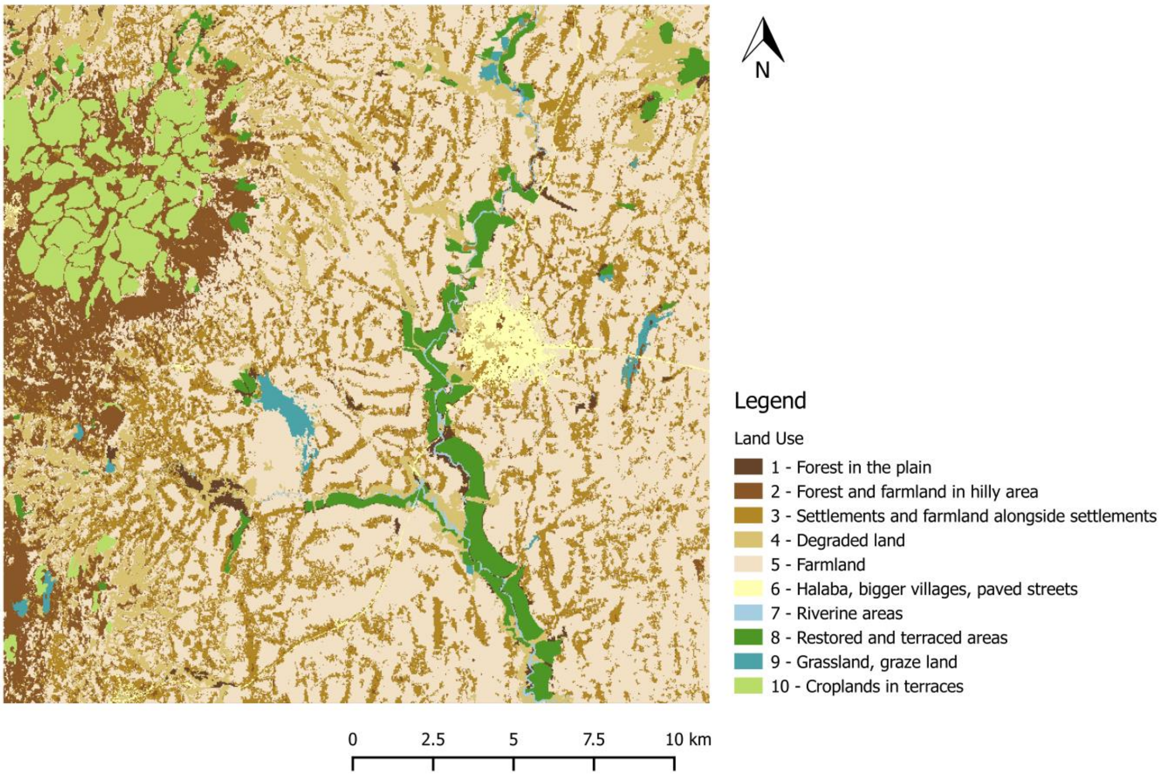

Figure 1. Land use classification derived overlapping the land use classification obtained through a supervised classification (see Chapter 3) and the conservation measures map (see Chapter 2).

Table 1. Characterisation and distribution of the land use classes of the land use classification used in the BBN model.

Land use class	Description	Coverage in km²	Percentage of study area (%)
1	Forests and exclosures in the riverplain	4.21	0.9
2	Forests and farmland in hilly area (mixed semi-natural and agricultural areas)	44.37	9.3
3	Settlements and farmland alongside settlements	86.16	18.0
4	Degraded land	39.88	8.4
5	Farmland	243.79	51.0
6	Halaba, bigger villages and paved streets	6.88	1.4
7	Riverine areas	2.26	0.5
8	Restored and terraced areas	18.02	3.8
9	Grassland, graze land	3.65	0.8
10	Croplands and agroforestry in terraces	27.09	5.7

2.2. Ecosystem Services modelling

The results of the ecosystem services (ESS) modelling presented in Chapter 2 (soil erosion/retention and nutrient export/retention) and Chapter 3 (carbon storage and sequestration) were used to populate the BBN conditional probability table to infer land degradation risk for each land use class (see Section 3.4.2). The data used to model the three ecosystem services were derived from a local survey on soil properties, from a supervised land use classification, and from global datasets (e.g. Landsat, MODIS, Sentinel 1 and Sentinel 2, WorldClim, ISRIC) (i.e. "hybrid" dataset). Further details can be found in Chapter 2 and Chapter 3.

2.3. Other spatial data

In order to infer land use change at a spatial level, the additional data used for mapping the probability of land degradation were:

- Slope that was calculated using the digital elevation map (DEM) at 30 m of resolution derived from the SRTM (Shuttle Radar Topography Mission) downloaded from the USGS (U.S. Geological Survey) (https://earthexplorer.usgs.gov/);
- Euclidian distance from degraded lands and settlements was calculated for each of the considered land use class (i.e. classes 3 and 6 for calculating the distance from settlements; and class 4 for calculating the distance from degraded lands);
- Inverse distance from forest edge obtained using an internal buffer approach;
- Settlements size to differentiate big rural settlements from small rural settlements (land use class 3). Big settlements were identified based on expert knowledge of the study area, and using Google Earth® images. The remained rural settlements were defined as small settlements.

See Section 3.2.1 for further details.

2.4. Qualitative data

Data from literature review and from a participatory approach developed during the summer 2016 were used in the BBN development and modelling, and to populate the conditional probability tables. In particular, they were used to inform scenarios development and the relative land use change patterns and likelihoods.

2.4.1. Literature review

The literature review was carried out in order to identify typical patterns of land use change in the Ethiopian landscape occurred in the last decades. The studies were selected in Google Scholar by using the following key words: land use change, Ethiopia, land use scenarios. Only the studies that presented similar characteristics to my study area were considered. The studies that didn't present the matrix of land use change were not considered. This was necessary in order to identify studies from which it was possible to derive explicit land use change trends and patterns during the past decades. 20 studies were examined (Tekle and Hedlund 2000; Garedew et al. 2009; Tsegaye et al. 2010; Mengistu et al. 2012; Meshesha et al. 2012; Kindu et al.

2013; Biazin and Sterk 2013; Teferi et al. 2013; Meshesha et al. 2014; Mekasha et al. 2014; Tesfaye et al. 2014; Wondrade et al. 2014; Gebreslassie 2014; Kebede et al. 2014; Molla 2015; Ariti et al. 2015; Wubie et al. 2016; Meshesha et al. 2016; Tolessa et al. 2017; Tadesse et al. 2017); the trends of cropland, woodland, settlements, forests, and grassland cover changes were considered.

The more plausible trends were identified and subsequently used to construct possible land use scenarios in the study area based also on population trends derived from the national and regional 1994 and 2007 census of the Central Statistical Agency of Ethiopia (Central Statistical Authority 1996; CSA 2007).

2.4.2. Participatory approach and scenarios definition

Information gathered during 33 small focus group discussions (FGDs) and during 32 semi-structured single interviews was used to inform the BBN structure and to populate the CPTs (see Section 3.2).

Of particular interest for this study were the FGDs on scenarios construction, where participants divided by gender were asked to produce possible and plausible scenarios derived from certain provided parameters. The groups were differentiated by gender to ensure the participation of women. The absence of men can helps to empower women and to increase their confidence in sharing their opinions (Chambers 1994; Evans et al. 2006). For the scenario construction objective, six FGDs with the local communities (3 female FGDs and 3 male FGDs), with 8-9 participants in each FGD, were carried out in the summer 2016. The participants were asked to draw and forecast possible future trends based on climate change, population growth patterns, changes in the land management, and in conservation measures implementation. After a short description of four different future changing patterns, the participants were asked to draw their future scenarios based on the given descriptions. Table 2 describes the parameters considered for the four future scenarios developed with the participatory approach.

Table 2. Description of the parameters considered in the four scenarios developed during the FGDs of the participatory approach. Based on these patterns the participants drew plausible scenarios to individuate the consequences of climate, population and land management at their *kebele* level.

	Parameters		
	Climate	**Population**	**Land management**
FGD Scenario A	Changes projecting forward the actual patterns of climate change	Continues growing	Steady – no changes from actual land management
FGD Scenario B	Changes projecting forward the actual patterns of climate change	Stabilises	Increase in conservation measure implementation
FGD Scenario C	Stabilises	Continues growing	Increase in conservation measure implementation
FGD Scenario D	Changes projecting forward the actual patterns of climate change	Continues growing	Increase in conservation measure implementation

Another FGD on scenarios construction was carried out also with five local experts of the Agricultural Office of Halaba to gather a different level of knowledge about the same possible scenarios.

For further details on the development of the participatory approach see Chapter 4, and participatory approach protocol in Appendix B.

3. METHODS

3.1. Bayesian Belief Networks (BBNs)

BBNs are probabilistic graphical models that consist of: i) a set of variables (nodes) with a set of mutually exclusive states, ii) a set of links representing causal relationships between the nodes that define their conditional dependencies and independencies in a form of a directed acyclic graph (DAG), and iii) a set of conditional probabilities tables (CPTs, one for each node) that define the belief that a certain node (children node) will be in a particular state, given the states of the nodes (parent nodes) that affect it directly. The strength of the probabilistic relationships among the different variables are inferred through CPTs (Cain 2001; Jensen and Nielsen 2007). CPTs are used to calculate and express the relationships between nodes (Pollino and Henderson 2010).

The DAG is characterised by a set of variables that are connected by arrows, which represent cause-effect relations. Each variable contains a limited number of mutually exclusive states, which is characterised by a probability that is set by the model developers, or using prior data and stakeholders' and experts' elicitation. The graph is acyclic, therefore feedback arrows from child nodes to parent nodes do not exist (Landuyt et al. 2013).

Parentless nodes can have i) unconditional probability if all the states have uniform distribution to represent complete uncertainty, or ii) a prior probability distribution based on prior knowledge. Child nodes have CPTs that represent the combinations of all states of its parent nodes (Marcot et al. 2006).

The BBN probabilistic representation can take into account and deal with uncertainty, hence, it represents an appropriate tool for modelling socio-environmental systems (Aguilera et al. 2011; Landuyt et al. 2013).

Fig. 2 shows the flowchart used in this study. The BBN development used data from:

- previous ecosystem services mapping (see Section 2.2);
- other spatial data and parameters (e.g. land use classification, slope, Euclidean distance from settlements, etc.) (see Section 2.3);
- experts and local knowledge gained during the participatory approach carried out in the summer 2016 (see Section 2.4.2 and Chapter 4);
- literature review for land use change scenarios development (see Section 2.4.1).

The CPTs were developed based on literature review, zonal statistical analysis, and expert local knowledge of the socio-ecosystem. The last step of the study was to perform the inference process of the probabilities on each pixel, to obtain the final spatial output (i.e. land degradation probability in four different scenarios) as probability of land degradation. See Sections below for further details on BBN development, CPTs completion, and scenarios construction.

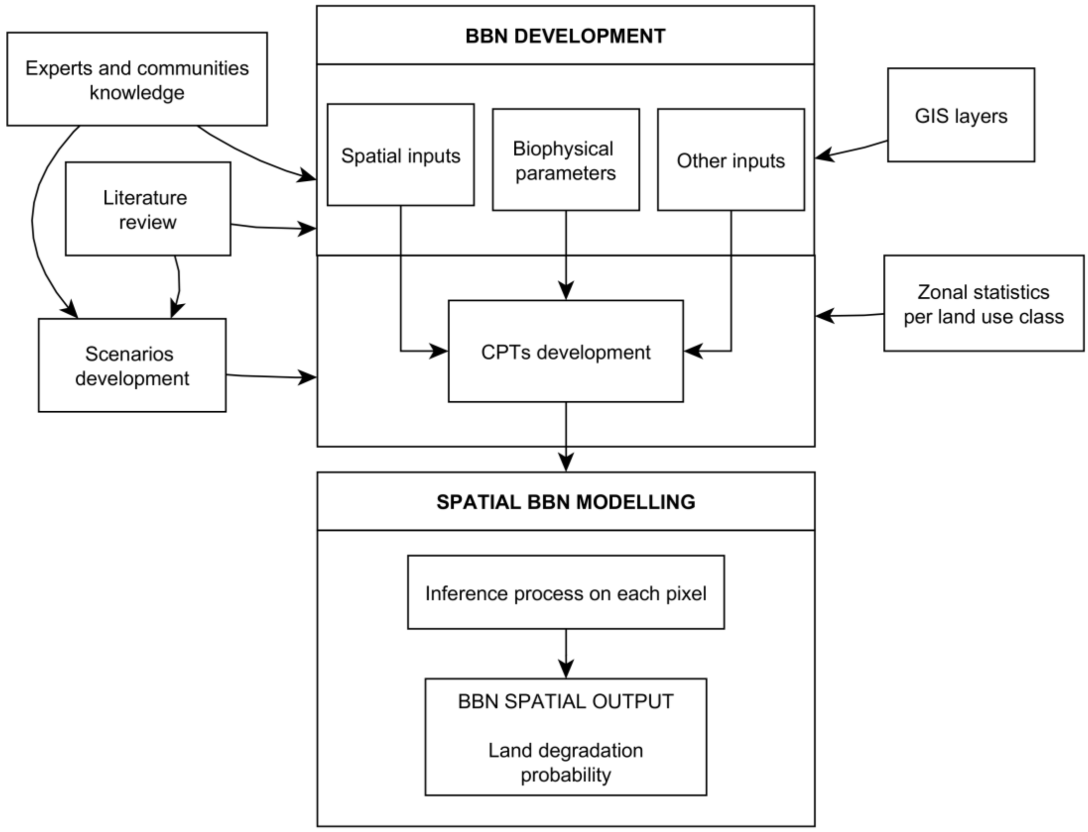

Figure 2. Flowchart. The BBN modelling was characterised by two steps. The first step was the BBN development with i) selection of nodes (spatial and non-spatial parameters) and ii) CPT completion and development with data from zonal statistical analysis, literature review, and local and experts' knowledge. The second step was the spatial BBN modelling that performed the inference of the probability at pixel level to obtain the final spatial outcomes: the land degradation probability.

In the Bayesian statistic, when dealing with uncertainty, the modeller can use subjective probability approach, based on personal and subjective beliefs and judgements, to derive the prior distribution and probability. This method is different from the objective approach, where repeated observations define the exact likelihood and frequency of the occurrence of a certain event or distribution (Schmeidler 1984; Chick 2006; Goldstein 2006; Jensen and Nielsen 2007). In this study, as in many other assessments of environmental systems that used the Bayesian Belief Network approach, the subjective probability approach, through expert judgements, was used to integrate quantitative knowledge or data (e.g. ecosystem services modelling results), and qualitative information (through literature review and participatory approach) for the conditional probability tables (CPTs) completion and development (Pollino and Henderson 2010)

3.2. BBN structure

Fig. 3 shows the BBN including non-spatial input variables (nodes, light grey), and spatial inputs variables (grey). The target output is the node land degradation probability (dark grey). The variables were selected considering the most important drivers of land use change as well as of land degradation exacerbation, derived from the local knowledge gained during the participatory approach (mainly the scenario construction FGDs) and through the literature review. The spatial nodes (see Section 3.2.1), used to infer land use change, were selected based on important features that mostly determine and affect land use changes' patterns. Moreover, the spatial nodes were used to infer land use change scenarios based on the patterns identified in the literature review and during the participatory approach discussions. Biophysical nodes (nutrient retention, carbon storage and sequestration, and soil erosion), derived from the results obtained in the ESS modelling presented in Chapter 2 and Chapter 3, were used to infer land degradation risk.

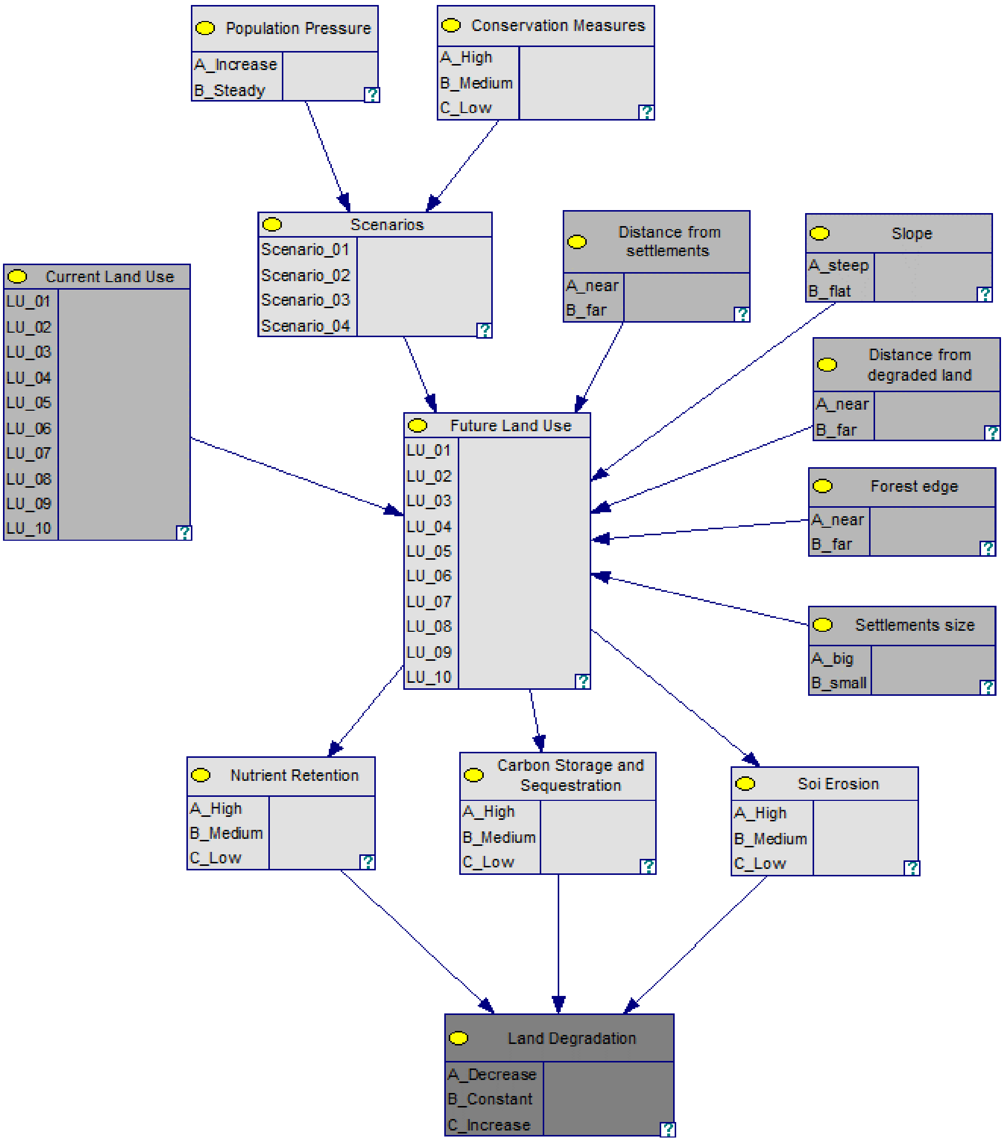

Figure 3. BBN structure. In light grey are reported non-spatial nodes (variables), in grey are reported the spatial nodes (variables) and in dark grey is reported the BBN outcome, e.g. the probability of land degradation (in three states: increase, constant and decrease).

3.2.1 Spatial nodes (inputs)

Table 3 describes the spatial inputs used in the BBN. The resolution of all the spatial variables was 30 m x 30 m. The spatial inputs were used to infer land use change for each scenario implemented (see Section 3.3), based on spatial patterns.

Table 3. Description and states of spatial variables (nodes). The GIS layers “distance from settlements” and “distance from degraded land” were calculated considering the Euclidean distance.

Spatial variables	Description	States
Current land use	Land use classification with 10 land use (LU) classes (see Section 2.1)	10 LU classes
Distance from settlements	Distance from land use class 3 (rural settlements) and 6 (urban settlements).	near (from 0 to 150 m); far (> 150 m)
Slope	Slope value in degrees of inclination from the horizontal (Horn 1981) calculated using the digital elevation map (DEM) downloaded from SRTM dataset.	steep (>10^0); flat (from 0 to 10^0)
Distance from degraded land	Distance from LU class 4 (degraded land)	near (from 0 to 120 m); far (> 120 m)
Forest edge	Inverse distance from the border of LU classes 1 and 8 (forested classes)	near (inverse buffer of 90 m); far (remained part of the forest; internal part)
Settlements size	Big settlements (apart from cities) were identified based on expert knowledge of the local area using Google Earth® images. The remained small settlements (LU 3) were defined as small settlements.	Big; Small

3.2.2. Non-spatial nodes (inputs)

The non-spatial variables used in the BBN structures were:

- Population pressure with two states: increase and steady. Scenarios with decrease of population pressure were not developed because, according to local experts, to the 1994 and 2007 Ethiopian census (Central Statistical Authority 1996; CSA 2007), and to the African statistics (African Development Bank Group 2017), the probability of the population pressure to decrease is highly unlikely, and population stabilisation represents a best case scenario;
- Conservation measure with three states: high, medium and low. This node identified different conservation measures implementation rates (see Section 3.3);
- Scenarios with four states to identify four scenarios based on the change on population pressure and on conservation measure implementation probability (see Section 3.3 for further details);
- Future Land Use with ten states as the number of land use classes. The CPT of this node was derived as in Section 3.3 and considering the spatial parents nodes (see Section 3.2.1 and Section 3.4.1);
- ESS and biophysical aspects that directly affect land degradation probability. Nutrient retention, carbon storage and sequestration and soil erosion were considered (see Section 2.2 and Section 3.4.2 for further details).

These five variables were the intermediate nodes (see BBN structure in Fig. 3 for further details).

3.3. Scenarios implementation

Four different scenarios were implemented in the BBN structure. The scenarios were identified based on literature reviews of Ethiopia land use change (see Section 2.4.1), and on local knowledge derived from several semi-structured interviews and focus group discussions (FGDs) carried out during April-June 2016 (see Section 2.4.2 and Chapter 4).

The drivers of the land use change were identified in i) population pressure and ii) conservation measures implementation. Conservation measures comprehended terraces in the slopes and restoration areas with terraces or soil bunds (e.g. exclosure). Population pressure and conservation measures' variables were selected because, during the participatory approach, they were identified as major factors affecting land degradation.

Climate change was not considered in this study; from runs of mechanistic models it was found that climate per se had less impact on ecosystem functionality, while land use change was identified as the major driver of land degradation exacerbation or alleviation (A. Gimona, personal communication). Therefore, climate change impacts were mainly mediated through land use change trends.

The increase in population pressures was supported by the Ethiopian census of 1994 and 2007 (Central Statistical Authority 1996; CSA 2007) and by the local perspective gained during the elicitation of local experts of the Halaba Agricultural Office and of the communities in the interviews and FGDs. The scenarios with stable population pressure were legitimated by the local experts of the Agricultural Office that forecasted possible stabilisation on population growth trends as a result of family planning programs. Table 4 summarised the considered BBN scenarios.

Table 4. Characterisation of the scenarios developed for the BBN modelling based on changes in population pressure and in conservation measures implementation.

Scenario	Population pressure	New conservation measure implementation
Scenario 1 (Sc1)	Increase	Medium
Scenario 2 (Sc2)	Increase	Low
Scenario 3 (Sc3)	Steady	Medium
Scenario 4 (Sc4)	Steady	High

Scenarios 3 and 4 assumed that the present restoration areas remain under conservation following the Agricultural Office experts' management guidelines and the study on exclosures in the same area (Byg et al. 2017) that stated the impossibility of the exclosures to be reconverted in croplands due to the Ethiopian legislation. However, in scenarios 1 and 2 due to increase in population pressure was assumed that conversion of part of the forested area could occurred, also according farmers and Agricultural Office experts that stressed how increase in population pressure could lead to deforestation despite the law and regulations. Land use transition matrices were developed based on the identified scenarios summarised in Table 4.

The transition probability matrices for each scenario (see Tables 5-8) were developed using the Markov chain model approach (Cox and Miller 1965; Castellazzi et al. 2008). Land use change from present to future was addressed using a transition probability matrix that gives the probability that a certain land use class will change to another class in the future (Kumar et al. 2014). The transition probability matrix can be developed using the following equation (Kumar et al. 2014):

$$P = P_{ij} = \begin{vmatrix} P_{11} & P_{12} & \dots & P_{1n} \\ \dots & \dots & \dots & \dots \\ P_{n1} & P_{n2} & \dots & P_{nn} \end{vmatrix} \quad (1)$$

where P is the probability from state i to state j. The equation must satisfy the following conditions: $\sum_{j=1}^{n} P_{ij} = 1$ and $0 \leq P_{ij} \leq 1$.

The transition probability matrices per land use class in each scenario are shown in Tables 5-8. A period of time of 30 years was identified as a plausible period of time for the occurrence of the trends identified in the four scenarios and in order to match with the restoration measures development. Therefore, the current land use reflected the current situation (year: 2017), and the future land use reflected possible scenarios (see Table 4) occurring in 30 years from the present (year: 2047). Refer to Table 4 for the description of the scenarios. The transition probability matrices were derived from the land use change patterns identified from the literature review and the participatory approach (see Section 2.4) and based on subjective expert knowledge and judgements (Chick 2006; Goldstein 2006; Jensen and Nielsen 2007; Pollino and Henderson 2010).

Table 5. Transition probability matrix per land use class in scenario 1. This scenario is characterised by forest reduction and conversion in cultivation. Part of the class 3 (settlement and farmland alongside them with homestead gardens) is transformed in more intensive cropland (land use class 5). Most part of the grassland is converted in cropland, and part is transformed in degraded land due to natural resources exploitation. Part of the degraded land is restored with implementation of soil and water conservation (SWC) measures. However, due to deforestation the degraded land will increase in other areas. There will be expansion of settlement in cropland areas. Some of the restored areas are converted back into cultivation determining also increase of degraded land.

Future LU (Sc1)	Current Land Use									
	1	2	3	4	5	6	7	8	9	10
1	0.2	0	0	0.3	0.5	0	0	0	0	0
2	0	0.5	0	0.2	0.3	0	0	0	0	0
3	0	0	0.7	0	0.1	0.2	0	0	0	0
4	0	0	0	0.65	0	0	0	0.35	0	0
5	0	0	0.2	0.2	0.6	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0
7	0	0	0	0	0	0	1	0	0	0
8	0	0	0	0.1	0.3	0	0	0.6	0	0
9	0	0	0	0.3	0.6	0	0	0	0.1	0
10	0	0.4	0	0.1	0	0	0	0	0	0.5

Table 6. Transition probability matrix per land use class in scenario 2. The scenario 2 is characterised by high deforestation rate with conversion of forests into croplands. Part of the rural settlement areas (class 3) is transformed in urban settlements and in a more intensive cropland. There isn't implementation of new SWC and restoration measures. Grassland is almost completely converted in cropland or degraded land. Restoration areas are converted into cropland leading to high land degradation rate because of the overexploitation of natural resources. The area undergoes high increment in cropland areas.

Future LU (Sc2)	Current Land Use									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	0.1	0	0	0.4	0.5	0	0	0	0	0
2	0	0.3	0	0.6	0.1	0	0	0	0	0
3	0	0	0.4	0	0.3	0.3	0	0	0	0
4	0	0	0	0.8	0.2	0	0	0	0	0
5	0	0	0.2	0.35	0.45	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0
7	0	0	0	0	0	0	1	0	0	0
8	0	0	0	0.3	0.4	0	0	0.3	0	0
9	0	0	0	0.35	0.6	0	0	0	0.05	0
10	0	0.3	0	0.5	0	0	0	0	0	0.2

Table 7. Transition probability matrix per land use class in scenario 3. Scenario 3 is characterised by protection of forest, restoration and exclosure areas, increase of woodland areas alongside the settlements, restoration of half of the degraded land. Also small part of the cropland is converted in woodland. Part of the grassland is converted into woodland and into cropland. Diversification of livelihoods characterised the scenario 3.

Future LU (Sc3)	Current Land Use									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	1	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0
3	0.2	0	0.8	0	0	0	0	0	0	0
4	0	0	0	0.5	0	0	0	0.5	0	0
5	0.1	0	0	0	0.9	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0
7	0	0	0	0	0	0	1	0	0	0
8	0	0	0	0	0	0	0	1	0	0
9	0.3	0	0	0	0.4	0	0	0	0.3	0
10	0	0.1	0	0	0	0	0	0.2	0	0.7

Table 8. Transition probability matrix per land use class in scenario 4. Scenario 4 is characterised by protection of forest, restored areas and exclosures. Some of the rural settlements areas (that comprehend homestead gardens and cropland close to the settlements) are converted into woodlands. Degraded land is almost entirely restored through implementation of SWC measures. Part of the cropland is transformed into restoration areas and part into agroforestry practices. Part of the grassland is converted into woodland. There is increase of terraces implementation in the hilly areas.

Future LU (Sc4)	Current Land Use									
	1	2	3	4	5	6	7	8	9	10
1	1	0	0	0	0	0	0	0	0	0
2	0	0.5	0	0	0	0	0	0	0	0.5
3	0.2	0	0.8	0	0	0	0	0	0	0
4	0.1	0.1	0	0.1	0	0	0	0.5	0	0.2
5	0	0.1	0	0	0.7	0	0	0.2	0	0
6	0	0	0	0	0	1	0	0	0	0
7	0	0	0	0	0	0	1	0	0	0
8	0	0	0	0	0	0	0	1	0	0
9	0.5	0	0	0	0	0	0	0	0.5	0
10	0	0	0	0	0	0	0	0	0	1

3.4. BBN parametrisation

3.4.1. Conditional probability tables

Data from i) literature review, ii) expert and communities' elicitation through the participatory approach, and iii) zonal statistics of ecosystem services modelling per land use class (refer to Chapter 2 and Chapter 3 for further details on ESS modelling) were used to populate and inform the Conditional Probability Tables (CPTs).

The CPT of the "future land use" node was the integration between the transition probability matrices developed to infer land use change (Tables 5-8), and other spatial nodes (e.g. distance from settlements, distance from degraded land, forest edge, settlement size, slope) and relative states, to address land use change based on spatial patterns. The nodes inferring the spatial patterns are described in Section 3.2.1. A matrix considering all the possible combinations of land use change and scenarios was developed. For each scenario and for each land use class the probability of changing into other land use classes was determined, by considering the transition probability tables previously described for each scenario (see Section 3.3), and the states of the spatial variables. This was possible by adding or subtracting a delta based on the likelihood of occurrence of a certain combination. The completion of the matrix (conditional probability table) must satisfy the rules of equation 1 (see Section 3.3). This method was used for all the 320 possible combinations in all the 4 scenarios. Thus, the CPT was completed informing the probabilities of change of each land use classes based on the scenarios considered and on the aforementioned spatial inputs. This approach enabled the BBN computation model to infer the land use changing patterns at a spatial level by cloning the BBN probabilities for each pixel.

To clarify, Fig. 4 shows some worked examples of four possible combinations, which considered the change in probability of land use class 1 (Fig.4a and 4b), and land use class 4 (Fig. 4c and 4d), from the “Current Land Use” node to the “Future Land Use” node, given certain status of the spatial nodes (e.g. distance from settlements, slope, etc.) in scenario 2.

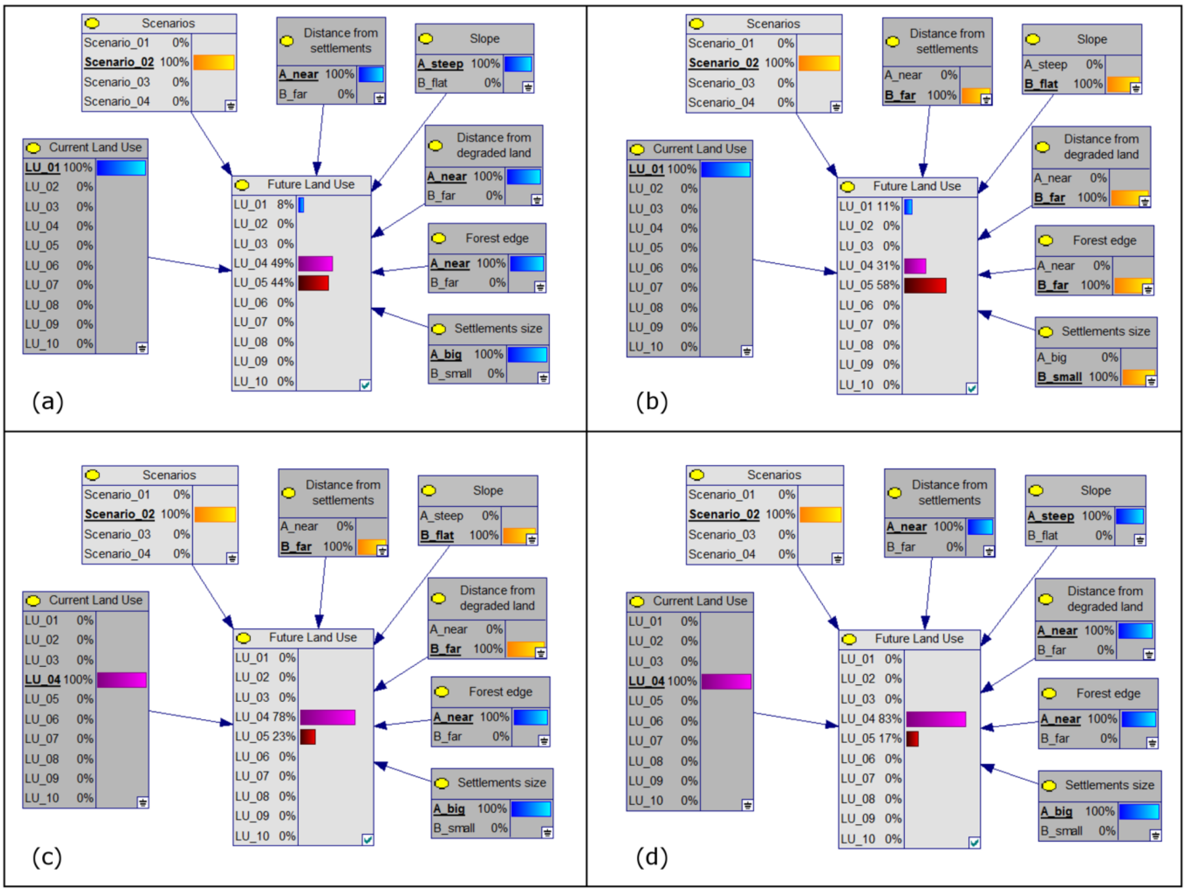

Figure 4. Worked examples of four possible combinations and the relative probability of “Future Land Use” node. In a) and b) an example of the change of probability of land use class 1, in scenario 2 and given certain spatial patterns (states of the spatial nodes; e.g. distance from settlements, slope, etc.). In c) and d) are presented the changes of probability in the “Future Land Use” of land use class 4 in scenario 2, given two different combinations derived from different status of the spatial nodes. The total possible combinations were 320 per scenario (and for each land use class).

3.4.2. Ecosystem services nodes

The ratio between the median of the whole area and the median of each land use class for each ecosystem service value was used to define the CPTs between the land use classes (states of “Future Land Use” node) and the three ESS/biophysical nodes (carbon storage and sequestration, soil erosion and nutrient retention). For each ecosystem service node, the highest probability to be “high” was assigned to the class with highest median of the service value; the corresponding probabilities for the states were: high=0.9; medium + low=0.1. The highest probability to be "low" was assigned to the class with lowest median; and the corresponding probabilities for the states were: high + medium=0.1; low=0.9. To assign the probabilities for the state "medium" the ratio between the quantiles of the whole areas and the quantiles of each land use class was used.

Table 9 presents an example of the completion of the states (high, medium, low) of the carbon storage and sequestration CPT. Class 10 was characterised by the highest ratio between the median of carbon storage and sequestration (t ha^{-1}) calculated in class 10 surface, and the median of the whole area. Therefore, the probability of carbon storage and sequestration in class 10 was assigned as high: 0.9, medium: 0.05, and low: 0.05. The same method was used for the other classes and also to populate the CPT of the soil erosion and the nitrogen retention. See Chapter 2 and 3 for further details on the ecosystem services mapping and modelling.

Table 9. Example of the completion of the CPT to define the probability of the three states (high, medium and low) for the carbon storage and sequestration. The median values (t ha^{-1}) of each land use class were sorted from the largest to the smallest. This helped to assign at the identified land use class the higher probability (state: high) and the lower probability (state: low) based on the derived list and on the ratio among median per land use class and median for the whole area. If the median value per land use class were comparable to the median in the whole area, higher probability was given to the "medium" state. The same approach was used to complete the CPT of nitrogen retention and soil erosion nodes.

LU class	Median (t ha^{-1})	25% percentile (t ha^{-1})	75% percentile (t ha^{-1})		Probability of carbon storage and sequestration (0-1)		
					High	**Medium**	**Low**
10	70.3	55.5	81.4	→	0.9	0.05	0.05
2	68.1	58.9	77.2	→	0.85	0.1	0.05
1	61.4	46.1	73.8	→	0.8	0.15	0.05
3	49.4	44.1	54.4	→	0.5	0.4	0.1
8	44.3	33.5	65.6	→	0.45	0.45	0.1
5	42.6	37.5	47.6	→	0.3	0.6	0.1
9	38.1	33.3	42.1	→	0.1	0.3	0.6
6	31.5	26.3	36.2	→	0.05	0.15	0.8
4	28.6	22.6	35.2	→	0.05	0.05	0.9
7	26.6	19.6	33.1	→	0.05	0.05	0.9
Whole area	44.5	37.5	52.5				

3.4.3. Land degradation node

Subjective judgement and expert knowledge were used to develop the CPT of the "Land Degradation" final node. Each combination of the states of the three ecosystem services/biophysical aspects nodes was considered. Table 10 shows an example of the matrix derived for the possible combinations considering the "soil erosion" to be "high". The same method was used for the other combinations, where state of "soil erosion" was either "medium" or "low".

Table 10. Worked example of the completion of the CPT of the "Land Degradation" node considering only the combinations obtained if the "Soil Erosion" state was "high". The approach of subjective probability was also used for the other possible combinations.

Soil Erosion		A_High								
Nutrient Retention		A_High			B_Medium			C_Low		
Carbon Storage		A_High	B_Medium	C_Low	A_High	B_Medium	C_Low	A_High	B_Medium	C_Low
Land degradation	A_Decrease	0.25	0.2	0.1	0.2	0.1	0.05	0.1	0.05	0.05
	B_Constant	0.5	0.5	0.3	0.5	0.4	0.15	0.2	0.1	0.05
	C_Increase	0.25	0.3	0.6	0.3	0.5	0.8	0.7	0.85	0.9

3.5. Final spatial outputs

Using the BBN tool BayesGIS (Gonzalez-Redin et al. 2016), spatial explicit outputs were obtained through evidence propagation of the probability among each variable on a pixel level. The tool supports the propagation of the BBN inference of each node for each pixel.

This enabled the BBN computation model to infer the land use changing patterns at a spatial level by cloning the BBN probabilities for each pixel. The final spatial output of the BBN modelling was the land degradation probability in three states: decrease, constant, increase.

Based on the scenarios implemented, four sets of maps were obtained, showing for each pixel of 30 x 30 m i) the probability of land degradation to increase, to remain the same (constant), or to decrease, and ii) the map showing the state of degradation (increase, constant, or decrease) with highest probability per pixel (each pixel returned the most probable state of land degradation).

3.6. Software used

For mapping the ecosystem services used to infer land degradation risk, the following open software and tools were used: Quantum GIS and GRASS GIS software (GRASS Development Team 2017; Quantum GIS Development Team 2017), and the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST, version 3.2.0) tool (Sharp et al. 2015), Nutrient Retention: Water Purification (see Chapters 2 and 3 for further details).

The GeNIe® 2.0 BBN Modeler software (BayesFusion LLC 2015) was used to develop the BBN structure and to populate the CPTs. R CRAN (R Core Team 2017) software was used for the statistical analysis and data preparation; in particular the following packages were used: "raster" (Hijmans 2015), "rgrass7" (Bivand 2015), "rasterVis" (Perpiñán-Lamigueiro and Hijmans 2013). The BayesGIS tool enables to propagate the probabilities and to calculate the BBN inference per pixel considering each node (variable). The BBN inference uses the following R packages: "bnlearn" (Scutari 2010), "gRain" (Højsgaard 2012), and "deal" (Gammelgaard Bottcher and Dethlefsen 2015).

4. RESULTS

4.1. Qualitative results

4.1.1. Literature review

Several studies identified a reduction of semi-natural vegetation (such as forest and woodland, shrubland, grassland) (Tekle and Hedlund 2000; Garedew et al. 2009; Meshesha et al. 2012; Kindu et al. 2013; Mekasha et al. 2014; Meshesha et al. 2014; Ariti et al. 2015; Wubie et al. 2016; Tolessa et al. 2017). Some studies recorded a reduction or a stabilisation on cropland expansion in the last decades following a high increase in the previous years (Teferi et al. 2013; Tesfaye et al. 2014; Tadesse et al. 2017; Tolessa et al. 2017), while others found that expansion of cropland area was still present (Garedew et al. 2009; Tsegaye et al. 2010; Meshesha et al. 2012; Haregeweyn et al. 2012; Kindu et al. 2013; Gebreslassie 2014; Wondrade et al. 2014; Ariti et al. 2015; Molla 2015; Meshesha et al. 2016).

Overall, the studies examined found a reduction in forest and grassland. This reduction characterised especially mixed agricultural ecosystems (Tekle and Hedlund 2000; Meshesha et al. 2012; Kindu et al. 2013; Meshesha et al. 2014; Wubie et al. 2016). Reduction of forest area and woodland was found by the majority of the studies considered (Tekle and Hedlund 2000; Tsegaye et al. 2010; Haregeweyn et al. 2012; Meshesha et al. 2012; Kindu et al. 2013; Mekasha et al. 2014; Tolessa et al. 2017). Plantation forests experimented an expansion in the last decades in some of the studies considered (Mengistu et al. 2012; Teferi et al. 2013).

Generally, all the studies considered found an increase in settlements cover. Increase in settlements cover was, in fact, reported by all the studies that considered the class settlements in the land use cover (Tekle and Hedlund 2000; Tsegaye et al. 2010; Kindu et al. 2013; Meshesha et al. 2014; Tesfaye et al. 2014; Meshesha et al. 2016; Tolessa et al. 2017).

An increase in bare land was also found by several studies (Meshesha et al. 2012; Teferi et al. 2013; Kindu et al. 2013; Gebreslassie 2014; Tolessa et al. 2017). However, others studies found a decrease in bare land distribution (Tsegaye et al. 2010; Molla 2015; Meshesha et al. 2016) For bare land different definitions were used; e.g. Teferi et al. (2013) considered bare land the “areas with little or no vegetation cover consisting of exposed soil and/or bedrock”. Meshesha et al. (2016) used a similar definition: “area with very little or no vegetation cover on the surface of the land. It consists of soil vulnerable to erosion and degradation. It also includes bedrock which is unable to support cultivation”. While Gebreslassie (2014) included bare land in the class “open land” that includes rocky areas, rural roads, and bare lands free of any use.

The bare land described by the aforementioned studies can be approximated with the degraded land (land use class 4) of the land use classification used in this study that comprehends area with little or no vegetation cover, gullies, and areas not favourable to support cultivation.

4.1.2. Participatory approach

Four scenarios were developed by the participants during the FGDs dedicated to scenarios construction. The scenarios were characterised by different trends in population pressure, climate change, and land management. They were used to develop the scenarios defined and used in the BBN.

For the FGD scenario A (which was characterised by population growth, climate change projecting forward the actual changing patterns, and no improvement of land management) all the participants of all the FGDs agreed that high degradation pattern will make the area unsuitable for human being. They forecasted high land degradation, conflicts for land shortage, deforestation of the remained forests, and food insecurity. High rates of migration were also forecasted by farmers participants, as well as by Agricultural Office experts.

For the FGD scenario B (population growth reduction, climate change projecting forward the actual changing patterns, and improvement of land management) two different point of views were found. Participant of the FGDs in Asore and in Layignaw Arsho identified this scenario as the best one among the 4 proposed scenarios. They stated that due to population pressure reduction and better land management it will be possible to tackle climate change impacts. However, different opinions were found in the Andegna Choroko FGDs (both in the female and in the male FGDs) and in the Agricultural Office experts' FGD. They stressed that, despite the reduction of population pressure and the better land management, there won't be environment or economic improvements, due to the adversely impacts of the climate change.

In the FGD scenario C (which was represented by population growth, stable climate, and better land management), apart from Andegna Choroko male FGD and Halaba Agriculture Office experts' FGD, the other FGDs' participants forecasted an increase of land degradation asserting that the population pressure is the main driver of land degradation. On the contrary, in the Agriculture Office experts' FGD and the Andegna Choroko male's FGD the participants asserted that with this scenario the environment will improve, and the area would undergo economic growth because of a stable climate and a better land management.

Finally, for the FGD scenario D (population growth, climate change projecting forward the actual changing patterns, and better land management) some participants stressed how the good land management will tackle land degradation caused by climate change and population pressure. During the male FGD in Layignaw Arsho the participants were also quite positive that a better land management and restoration implementation will lead to better micro-climate leading to a win-win situation. Other participants stressed that the environment conditions will get worse due to the adversely impacts of the population pressure. The majority of the participants agreed that the land management will be affected by population pressure together with the harmful impact of climate change, leading to an overall increase of land degradation. Fig. 5 shows an example of the outcomes of the scenarios FGD exercise. In particular, in the picture it is shown the FGD scenario D drew by the male participants of the FGD in Layignaw Arsho.

To conclude, the farmers generally recognised the population growth as main factor in land degradation exacerbation, even comparing it to climate change. Participants stressed how climate change cannot be controlled, whereas population can be controlled through contraceptive methods, as well as family planning. Accordingly, they highlighted the importance of family planning in reducing and tackling land degradation.

The Agricultural Office experts asserted that the better scenario was the FGD scenario C (better climate condition and population growth). To summarised they highlighted that "*we can control and tackle population pressure impacts by implementing a better land management, but climate change and its adverse impacts are difficult to control and to tackle*".

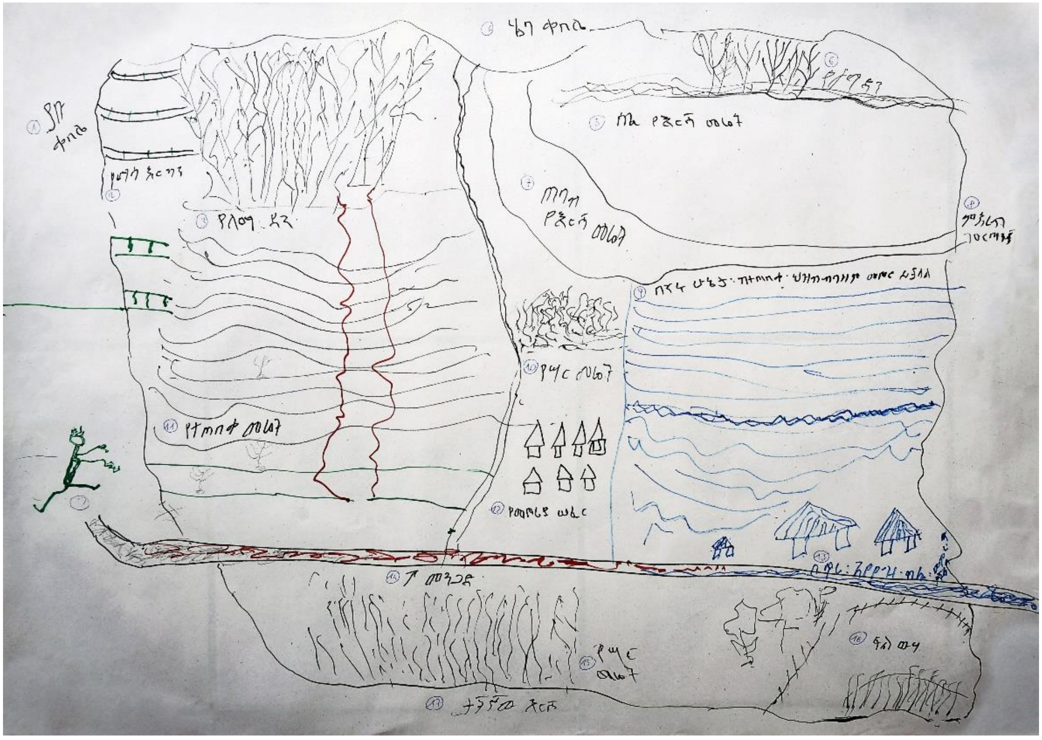

Figure 5. Flipchart of FGD scenario D drew by the male participants of the Layignaw Arsho FGD.

4.2. Spatial BBN outcomes: land degradation probability

The BBN modelling, through the BayesGIS tool, returned spatial outputs from which it was possible to infer land degradation probability to: i) increase, ii) remain the same (constant), and iii) decrease, at a pixel level and in the four scenarios. The map indicating the state of land degradation with highest probability (decrease, constant, increase), per pixel of 30 x 30 m resolution, was also obtained for each scenario.

The median for the whole area of the probability of a decrease in land degradation was 0.31, 0.26, 0.28, and 0.41 in scenario 1, scenario 2, scenario 3, and scenario 4, respectively. Fig. 6 shows the probability of a decrease in land degradation in the four scenarios.

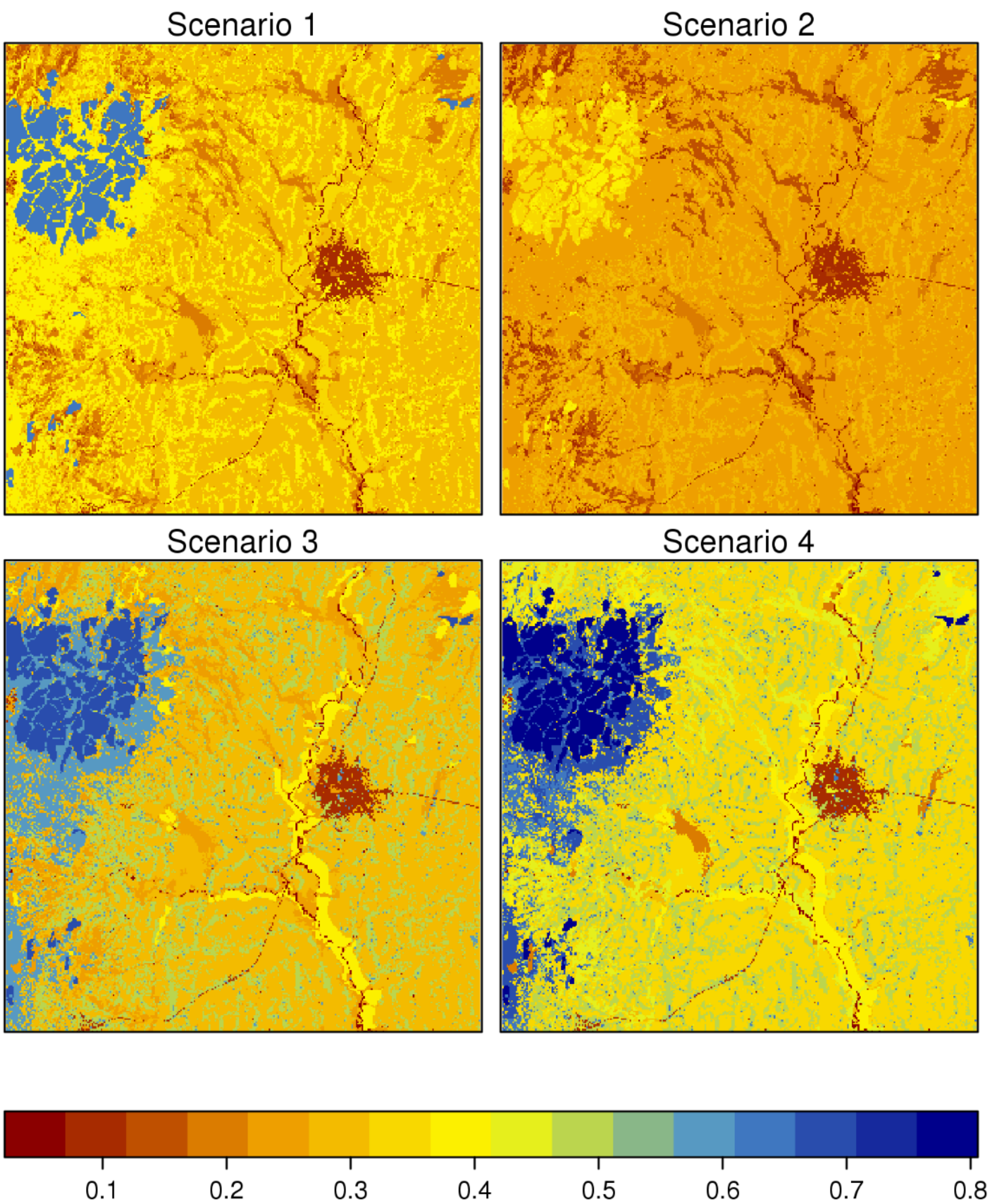

Figure 6. Maps of the probability of a decrease in land degradation in the four scenarios.

It is possible to see how the probability of a decrease in land degradation changed due to the land use class and due to the change in scenario. High probability of decrease was found generally in the hilly area characterised by higher vegetation cover. Low probability of decrease was found in the urban settlement (especially Halaba city), riverine areas and degraded land. Different level of probability of decrease of land degradation was found based on the scenario considered.

The median for the whole area of the probability of an increase in land degradation was 0.38, 0.47, 0.36, and 0.32 in scenario 1, scenario 2, scenario 3, and scenario 4, respectively. However, aggregated statistics masked the spatial variability conveyed by the maps, that can instead show the spatial distribution of land degradation risk. Fig. 7 shows the probability of land degradation to increase for each scenario.

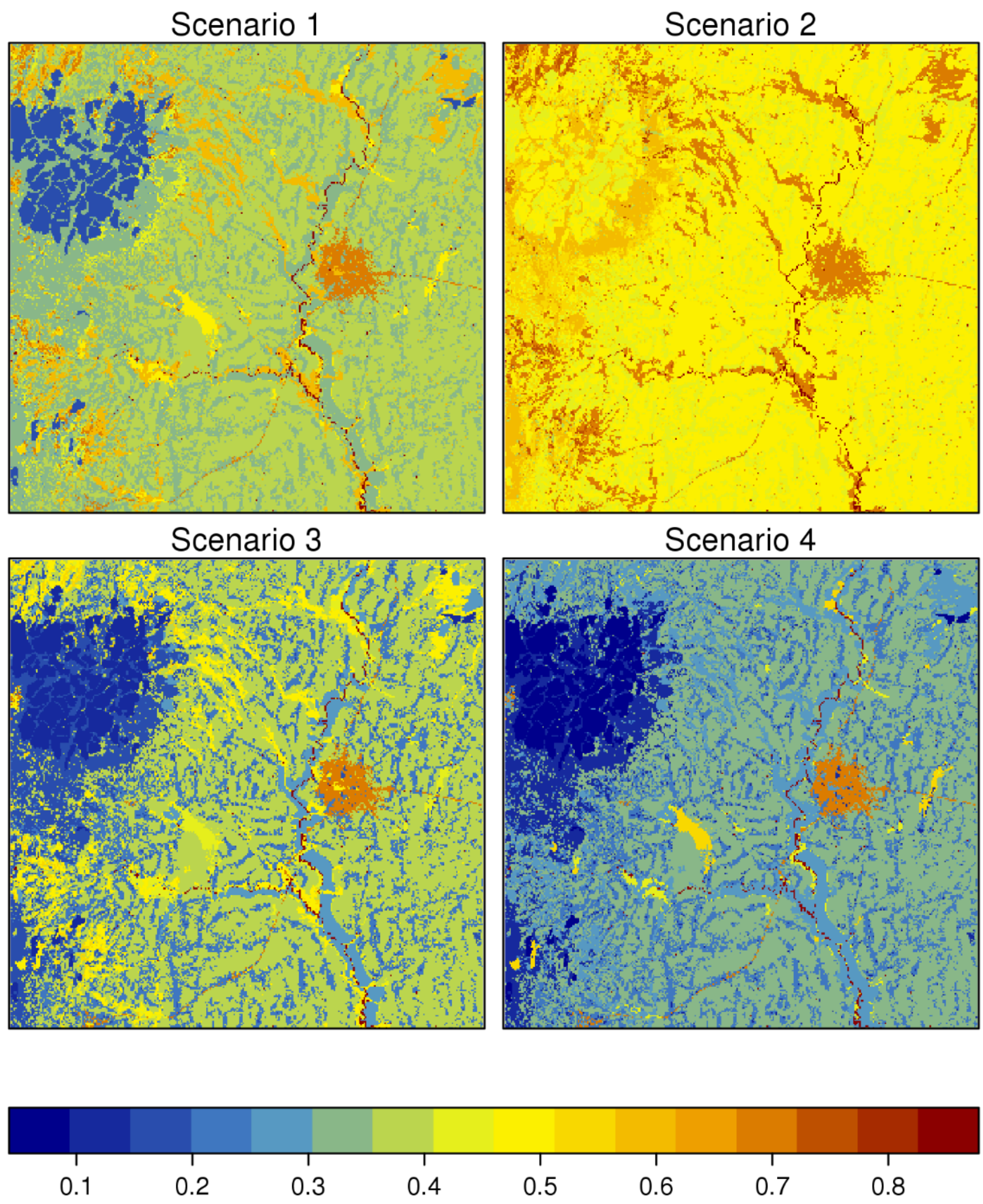

Figure 7. Maps of the probability of increase of land degradation in the four scenarios.

Also in this case, it is possible to notice a pattern linked to the land use class distribution. This was because the main spatial input in the BBN model was represented by the land use map with other spatial input maps to infer land use change. Land degradation risk was inferred based on the statistic (per land use class) of carbon storage and sequestration, soil erosion and nutrient retention (see Table 10).

The histograms in Fig. 8 show the distribution of probability, by grid cell, of increase of land degradation in the whole area in the four scenarios. The distribution changed based on the scenarios, showing that the probability of increase of land degradation was higher in scenario 2, while scenario 4 showed lower value of probability of increase.

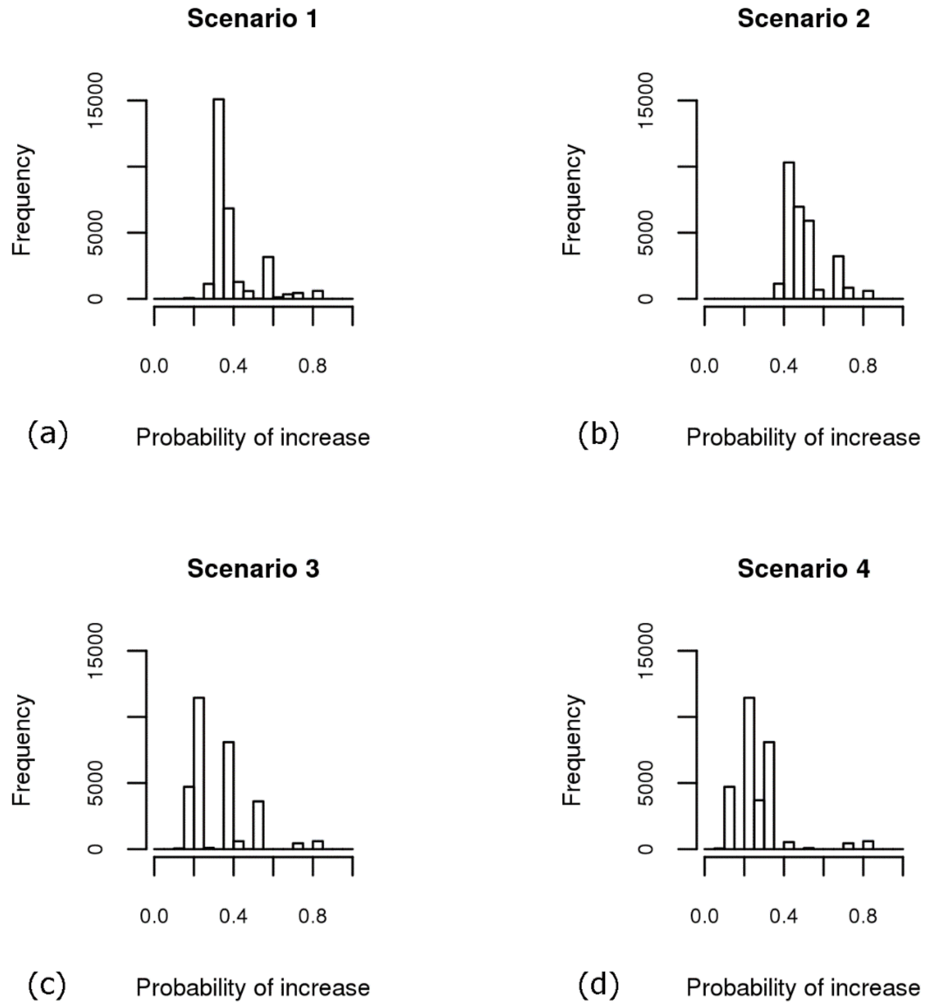

Figure 8. Histograms of probability of increase of land degradation in scenario 1 (a), scenario 2 (b), scenario 3 (c), and scenario 4 (d).

Table 11 shows, for each land use class, in each scenario, the percentage of the area covered by a probability of increase of land degradation higher than 0.33, higher than 0.50, and higher than 0.66. The distribution of probability of an increase of land degradation higher than 0.33 was high in almost all the land use classes in almost all the scenarios (apart from scenario 4). The area characterised by probability of increase of land degradation higher than 0.66 was instead quite low if classes 6 and 7 were not considered. Just in scenario 2, the class 4 (degraded land) showed probability of increase of land degradation higher than 0.66 in 100% of the covered area. Concerning land use 4, in the other scenarios, the probability of increase of land degradation was lower because of the assumption of an increase of restoration and conservation activities in part of the degraded land (see Section 3.3 on scenarios implementation).

Table 11. Percentage of area of each land use class where the probability of increase of land degradation was higher than 0.33, 0.50, and 0.66 in the four scenarios considered.

Land Use class	Probability of land degradation to increase											
	> 0.33				> 0.50				> 0.66			
	Sc1 (%)	Sc2 (%)	Sc3 (%)	Sc4 (%)	Sc1 (%)	Sc2 (%)	Sc3 (%)	Sc4 (%)	Sc1 (%)	Sc2 (%)	Sc3 (%)	Sc4 (%)
1	100	100	100	100	3.9	100	0	0	0	0	0	0
2	50.8	100	0	0	0	100	0	0	0	0	0	0
3	0	100	0	0	0	0	0	0	0	0	0	0
4	100	100	100	0	100	100	100	0	11.5	100	0	0
5	100	100	100	0	0	3.6	0	0	0	0	0	0
6	100	100	100	100	100	100	100	100	100	100	100	100
7	100	100	100	100	100	100	100	100	100	100	100	100
8	100	100	0	0	0	0	0	0	0	0	0	0
9	100	100	100	100	12.7	100	0	100	0	0	0	0
10	0	100	0	0	0	0	0	0	0	0	0	0

Fig. 9 shows the bar plot of the median probability of increase of land degradation per land use class in the four different scenarios (scenario 1 in blue, scenario 2 in green, scenario 3 in yellow, and scenario 4 in grey). Class 6 (urban settlements and paved streets) and class 7 (riverine areas) had the same probability of increase of land degradation in all the four scenarios because it was assumed that no change of management would affect these land use classes in the different scenarios. The other classes showed different probability of increase of land degradation because of the change in land management due to changes in population pressure and conservation measures implementation. Overall, scenario 2 showed higher values of probability of increase of land degradation in all the land use classes. Lower values of probability of increase of land degradation were generally found in scenario 4. Intermediate values were instead found in scenarios 1 and 3.

Fig. 10 shows the highest probability of land degradation in the whole area for the 4 scenarios; in white is represented the area where the most probable state of land degradation is decrease, in light grey the area where the most probable state of land degradation is constant, while in dark grey the area where the most probable state of land degradation is increase. In scenario 2, in the whole area, the highest probability of land degradation is to increase, meaning that in each pixel the probability of land degradation to increase was higher as compared to the probability to decrease or to remain constant. The probability of increase of land degradation decreased substantially in scenario 3 but especially in scenario 4. Fig. 11 shows the bar plot of the distribution of the most probable state of land degradation for the whole area in the four scenarios (Sc1-4). The same colours of the maps in Fig. 10 are used also in Fig. 11: white (decrease), light grey (constant), dark grey (increase).

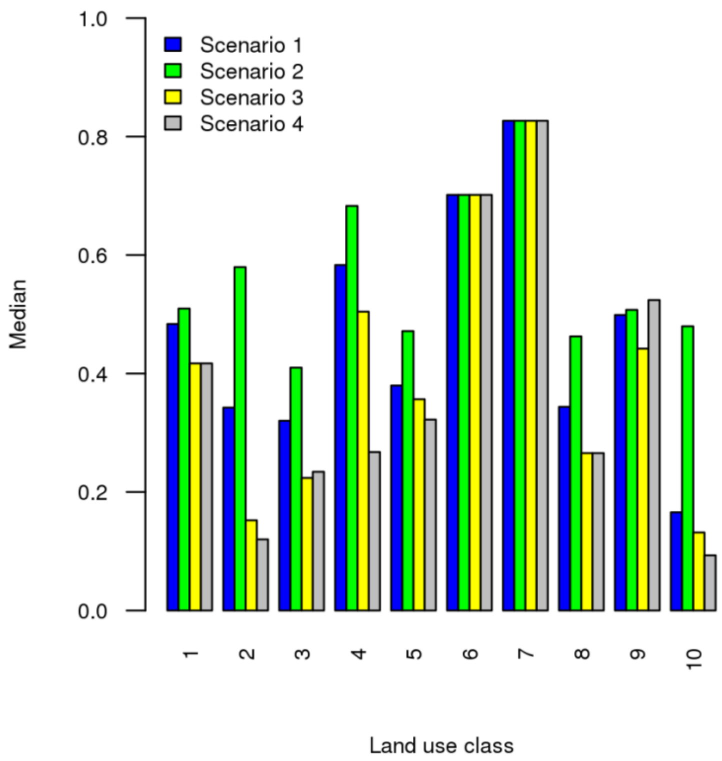

Figure 9. Probability of increase of land degradation per land use class in each scenario

To summarise, the most vulnerable classes across scenarios were the number 4 (degraded land), 6 (urban settlements), and 7 (riverine areas) (see Fig. 9 and Table 11). The riverine areas (land use class 7), although represented a small part of the whole study area, were in fact, characterised by low carbon storage and sequestration, high soil erosion. and low nutrient retention. The urban settlements (land use class 6) are characterised by very low carbon storage and sequestration and nutrient retention and also high soil erosion due to the lack of vegetation cover. The already degraded areas (land use class 4) were highly subjected to an increase of land degradation risk especially in scenario 2 and scenario 1, whereas the probability of an increase of land degradation risk highly decreased in scenario 4, because of the assumption of high probability of implementation of restoration activities. The lower probability of an increase of land degradation was, with different ranges, found in the north western hilly area, in all the scenarios (apart from scenario 2) (see Fig. 7 and Fig. 10). The hilly area is mainly covered by the land use classes 2 and 10, characterised by higher vegetation cover and by agroforestry practices often in terraces.

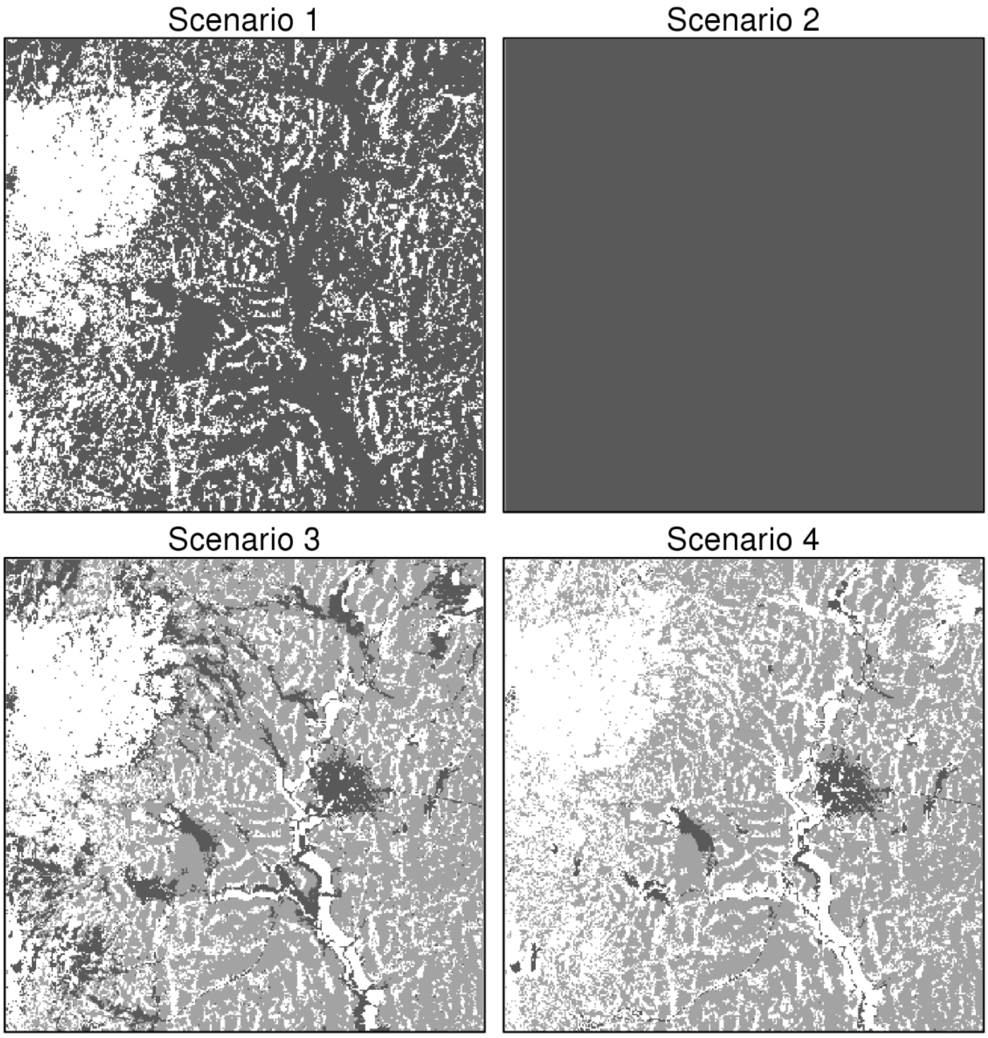

Figure 10. Spatial distribution of the most probable state of land degradation in each scenario. The states are represented by different colours (white: decrease, light grey: constant, dark grey: increase).

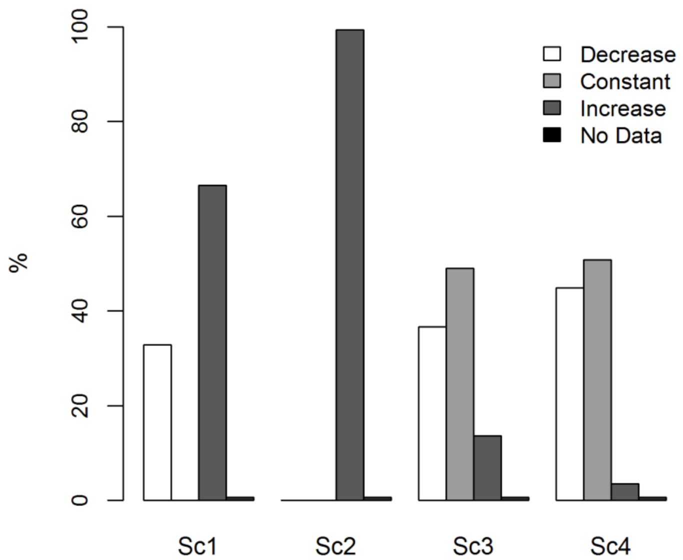

Figure 11. Distribution of the most probable state of land degradation in each scenario. The different states are identified in white (decrease), light grey (constant), and dark grey (increase). No data are shown in black.

5. DISCUSSION

5.1. Land degradation risk in the study area

The method developed in this study could provide a good means for identifying land degradation patterns so that a "rapid" synthesis of areas and scenarios likely linked to land degradation risk can be identified. This method can give decision-makers an effective means for suggesting where and how to intervene to promote a sustainable land management to reduce land degradation. However, the method developed was not intended to replace empirical field researches on effective land degradation quantification.

This study supported the identification of priority areas for intervention. This was possible also by implementing different scenarios of land use change, derived from different patterns of population pressure and conservation strategies. Furthermore, the integration of the BBN model together with GIS tools enabled to identify the probability of land degradation risk at a spatial level. The possibility of propagating the probability of change at a spatial level was feasible thanks to the integration of GIS and BBN. Therefore, this study concurred with Phan et al. (2016) that pointed out the effectiveness offered by linking spatial data with BBNs models.

The advantage of combining empirical data with expert knowledge and local community elicitation information, and the possibility of bearing in mind uncertainty, was an advantage for assessing a complex aspect (Cain 2001; Marcot et al. 2006; McCann et al. 2006; Aguilera et al. 2011; Landuyt et al. 2013), such as land degradation risk. Moreover, by inferring land degradation risk from the previously mapped carbon storage and sequestration, soil erosion and nutrient retention (see Chapter 2 and Chapter 3), BBN provided the means for a more reliable underpinning to estimate land degradation risk, considering different aspects that together contribute to land degradation alleviation or exacerbation, such as soil erosion, carbon stocks, nutrient retention, and conservation measures implementation.

Thus, this study mapped land degradation risk occurred under different land management and population pressure scenarios. The obtained results can be useful for prioritising certain areas for restoration interventions, as well as to identify possible consequences based on scenarios development. The possibility to calculate the probability of the parent nodes, given the value of their children nodes, is also an advantage for identifying causal relationships between causes and consequences. This enables to deduce the probabilities of different causes given the consequences (Uusitalo 2007). This could be relevant if policy and decision-makers aim to prioritise a certain scenario and want to know the best approach to obtain the selected scenarios' outcomes. Accordingly, if one scenario outcomes should be prioritised, the decision-makers could identify the possible drivers that lead to the selected scenario. The BBN approach used in this study facilitated the representation of potential outcomes of different management options and strategies, hence, it could help decision-makers in suggesting plausible management strategies (Cain 2001; McCann et al. 2006).

The integration of GIS and BBN tools enabled to obtain spatial explicit outcomes, identifying the areas more prone to land degradation. BBNs models have another advantage: new data and information (e.g. new variables) can be integrated in the structure, in subsequent moments, to update the results (Celio et al. 2014). This flexibility represents a great advantage when dealing with complex systems such as agroecosystems, and with complex subjects as land degradation risk. For example, this aspect could enable me, in the future, to increase the complexity of the BBN structure by adding new variables. Additionally, the use of the BBN modelling enables an effective and explicit communication of different possible outcomes, that can be understandable also for non-modellers, and for people without technical skills (Cain 2001; McCann et al. 2006).

In this study, for example, a land use change scenario could be targeted in order to address the desired outcomes. In order to highly reduce land degradation risk, decision-makers could try to address a reduction of population pressure and a better land management with intensive implementation of conservation measures, such as exclosures and terraces. Moreover, decision-makers might prioritise and target cultivated area (especially in the plain), and especially the steep area that are highly susceptible to soil erosion and land degradation. The more vegetated hilly area, in the north-western part of the study area, could be targeted in order to promote the maintenance, or the improvement of the current farming system characterised by agroforestry practices in terraces fields.

Although land degradation is a complex problem, and more variables and aspects could be considered in the BBN modelling, the method presented in this paper could represent a rapid appraisal for a decision-making process. The implementation of the scenarios was useful to get a glimpse of the seriousness of the problem. This is particularly evident from Fig. 11 that shows the spatial distribution of the most probable state of land degradation in the four scenarios. It was found that in scenario 2, in the whole area, the most probable state of land degradation was to increase. This type of results should help to acknowledge the need of urgent measures for promoting sustainable management, by considering also developing strategies to target the communities involved in and affected by land degradation exacerbation. Therefore, these BBN results could suggest at a decision-making process the possible coping strategies to adopt in order to alleviate land degradation. An ambitious goal could be represented by the Zero Net Land Degradation (ZNLD) target (Lal et al. 2012; United Nations 2012; UNCCD 2012). In order to achieve ZNLD, new restoration areas should be established. Agroforestry practices might be suggested at a decision-making process, because they facilitate the diversification of livelihoods, and help in building livelihoods resilience to flood and drought (Leakey et al. 2005; Quinion et al. 2010; Quandt et al. 2017; Kassie 2017). Moreover, agroforestry practices support carbon sequestration (Albrecht and Kandji 2003; Lal 2004; Mutuo et al. 2005; Atangana et al. 2014) and soil restoration, through reducing soil erosion and improving nutrient cycling (Young 1989; Lal 1989; Roose and Ndayizigiye 1997; Atangana et al. 2014; Hillbrand et al. 2017). Accordingly, the north-western hilly area, which is characterised by mixed agriculture with woodland in terraces, and where agroforestry practices are more common (as compared to the plain areas), showed lower probability of increase of land degradation (see Fig. 7), and higher probability of decrease of land degradation (see Fig. 6), in all scenarios. Furthermore, Fig. 11 shows that in the hilly area the most probable state of land degradation was to decrease, apart from scenario 2, where in the whole area the most probable state of land degradation was to increase.

Land degradation assessments should be mindful that a sustainable management must consider people needs especially in developing countries, where the majority of the inhabitants rely upon natural resources availability. The straightforward solution at land degradation should indeed comprehend massive implementation of restoration programs, both at local and at national scale. However, the increasing population pressure in Ethiopia poses the problem of achieving food security. Therefore, care should be used when spatial assessments aim to inform decision-making strategies, for reducing land degradation without depleting community livelihoods availability.

In the study area, several restoration areas have been already established (Yirdaw et al. 2014; Byg et al. 2017). However, it was found that the area continued facing intense land degradation (see also previous Chapters). Therefore, there is the need to act in order to reverse this path, for securing land productivity and promoting human well-being, by securing the diversification of the livelihoods. In this respect, a suggested intervention could be the extensive application of agroforestry practices together with application of organic and inorganic inputs.

From this study results, the role of population growth in affecting the environment was clearly shown. The scenarios which presented a stable population pressure (scenarios 3 and 4) were indeed characterised by reduced probability of increase of land degradation (see Fig. 7 and Fig. 10). Accordingly, population growth could also in the future pose a serious risk for land degradation exacerbation, if sustainable management and conservation programs are not widely adopted. This aspect concurred with other Ethiopian studies that pointed out the serious threat on land management sustainability, and on human well-being, posed by the intense population growth that is affecting Ethiopia (Hurni 1993; Desta et al. 2000; Nyssen et al. 2004; Girmay et al. 2008; Meseret 2016). Population growth had indeed caused high rate of deforestation, natural resource exploitation, overgrazing, expansion of farmlands in marginal land (Grepperud 1996; Hurni et al. 2005; Lemenih et al. 2014; Zewdie and Csaplovics 2015). Also the farmers interviewed during the FGDs identified the population growth as one of the main drivers of land degradation throughout the past years. In Halaba *woreda*, an overall increase of 22% in population was registered from the 1994 to the 2007 census, with 38% increase of urban population, and 17% increase of rural population (Central Statistical Authority 1996; CSA 2007).

Nonetheless, the expert of the Agricultural Office asserted that an increase of population pressure could also be an advantage in order to restore the degraded land through intense public programs of land restoration. Although the increase in labour force could definitely lead to an increase in implementation of public watershed conservation measures, the majority of studies considered didn't mentioned population growth as one of the crucial positive aspect in watershed conservation plans and implementation. It was instead stressed how watershed conservation measures were mainly adopted, after serious famines through food for work projects (Campbell 1991), to stop the degradation caused by intense population growth (Alemayehu et al. 2009), and subsequently alleviate food shortage. Moreover, despite the larger labour force available, larger family size could represent a hindrance to implement SWC measures in the household's plot because of the shrinking plot's size

(Shiferaw and Holden 1998; Bekele and Drage 2003; Amsalu and de Graaff 2007). Furthermore, Hurni (1993) showed that, without emphasis on family planning strategies, achieving a long-term sustainable use of natural resources in Ethiopia is highly unlikely.

5.2. Relevant qualitative information on land use change in Ethiopia

In Ethiopia, in the past decades, land use change patterns indicated an overall natural resources exploitation. Accordingly, a widespread deforestation was found in several areas in Ethiopia (Tekle and Hedlund 2000; Garedew et al. 2009; Meshesha et al. 2012; Kindu et al. 2013; Mekasha et al. 2014; Ariti et al. 2015; Wubie et al. 2016; Tolessa et al. 2017). The loss in forest cover and in semi-natural vegetation followed a relevant increase in farmland. In most of the studies considered, the increase in farmland area continued also in the more recent years (Garedew et al. 2009; Tsegaye et al. 2010; Meshesha et al. 2012; Haregeweyn et al. 2012; Kindu et al. 2013; Gebreslassie 2014; Wondrade et al. 2014; Ariti et al. 2015; Molla 2015; Meshesha et al. 2016), whereas in other areas, in the recent years, a steady trend was observed (Tsegaye et al. 2010; Meshesha et al. 2012; Kindu et al. 2013). Hence, in most of the studies considered, the rate of cropland increase followed a certain pattern: high increase in the 70s and 80s, and decrease in the more recent decades. This was mainly due to the fact that some areas were intensively exploited in the past, hence, they have already reached the maximum available croplands expansion, by converting also marginal areas into intensive croplands, leaving no other areas suitable for croplands (Teferi et al. 2013; Tesfaye et al. 2014). Other areas were still undergoing vast land use changes at the time of the study, with reduction of semi-natural vegetation and high increase in cropland areas (Tsegaye et al. 2010; Meshesha et al. 2012; Kindu et al. 2013). According to the local farmers interviewed during the FGDs, also in their *kebeles* the land suitable for cultivation has already been transformed, leaving no more available land. Therefore, the local farmers indicated land shortage and small land size per household as key issues for sustaining their livelihoods and their general well-being.

On the other hand, some studies found a moderate increment on forest surface (Mengistu et al. 2012; Tesfaye et al. 2014; Meshesha et al. 2016). In the last decades, in large areas of Ethiopia, restoration programs were launched in order to stop the high soil erosion, and the loss of soil fertility. The forest modest increment could be derived from implementation of conservation programs that involved development agents and the all communities (Molla 2015; Meshesha et al. 2016). Furthermore, other studies (Hurni et al. 2010; Tesfaye et al. 2014) stressed that the increase in forest and plantation cover has to be found in the national conservation efforts that followed the severe famines of 1972/73 and 1985/86.

As pointed out before, also in the Halaba *woreda*, several areas have been restored and several terraces have been constructed. This has resulted to an increase in soil quality and fertility of the restored area, as well as soil erosion reduction. The farmers perceived the restoration area as important conservation measures for preserving the environment (Byg et al. 2017). Nonetheless, the study of Byg et al. (2017), which evaluated the distribution of services and disservices of three restoration areas (exclosures), found that such restoration programs often fail to couple conservation efforts with development goals aiming to increase livelihoods and general well-being, and overall alleviate poverty. One of the crucial dis-benefits indicated by the farmers was especially the damage caused by wild animals, that find in the exclosure the suitable habitat (Byg et al. 2017).

Even though not all the studies indicated or addressed the drivers of change of land use cover, it was possible to identify the major causes of these changes. Some studies indicated the population growth as major drivers (Wondrade et al. 2014; Kebede et al. 2014; Gebreslassie 2014; Molla 2015; Meshesha et al. 2016), others indicated political and tenure policy changes as key factors in affecting the land use (Mekasha et al. 2014; Gebreslassie 2014; Tesfaye et al. 2014; Wubie et al. 2016). In fact, the changes on the land policy of the last decades, and especially between the Imperial regime and the Derg regime, constituted a crucial driver in determining landscape and land use changes. The Derg regime, by stabilising and nationalising the land tenure, supported a change on farmers' habits. Farming activities were incentivised, while pastoralism activities and people mobilisation was restrained (Byg et al. 2017).

Furthermore, many studies found an increase in settlements distribution (Tekle and Hedlund 2000; Tsegaye et al. 2010; Kindu et al. 2013; Meshesha et al. 2014; Tesfaye et al. 2014; Meshesha et al. 2016; Tolessa et al. 2017), confirming the trends of population growth in Ethiopia reported by the national census in 1994 and 2007, and by the African Statistical Yearbook 2017 (Central Statistical Authority 1996; CSA 2007; African Development Bank Group 2017).

During the FGDs, almost all the participants stressed that the solutions to reduce and alleviate land degradation would be to: i) use family planning in order to reduce population pressure indicated as major cause of land degradation, ii) implement better land management practices and measures (such as terraces), and iii) conserve the forest remained to reduce soil erosion. However, other farmers asserted that "*First of all we pray God for asking better climate conditions*" and then "*we ask the government for help*". Moreover, the several FGDs conducted indicated that some households relied on food aids and did not consider other coping strategies during harsh period (especially droughts). This "attitude" of waiting for government help and aids could be derived from the fact that, in the past years, the study area communities suffered harsh periods, and also because of the absence of valid alternatives (such as farming diversification and intensification, off-farm activities and employments) for coping with unreliable climatic patterns and intense degradation. During the 2015, the farmers endured harvest failure due to strong drought. The following year (2016), the area was instead interested by later and intense rainfalls, which led to several floods, and also by a following drought (FAO 2017). Thus, during the FGDs, the farmers were particularly sensitive to climate change impacts, and they highlighted the absence of valid alternatives, apart from adopting better land management. However, the participants also asserted that participating to the collective food for work programs, such as PSNP (Productive Safety Net Programs), often creates dependence syndrome, preventing them to construct conservation measures if they are not rewarded with aids.

Finally, the majority of farmers identified the population growth as major drivers of land degradation, due to its impacts on land management and activities, and on natural resources exploitation. The findings of the participatory approach developed in this study concurred with other studies that highlighted the harmful impacts of the population growth in the Ethiopian landscapes (Hurni 1993; Desta et al. 2000; Hurni et al. 2005; Gebreslassie 2014).

Furthermore, during several FGDs, the farmers stressed that if the population growth continues, they will be forced to cut the remained forests and restoration areas in order to obtained more cultivable land, even though it is not allowed by law. Hereafter, addressing the population growth issue appears to be a crucial step in order to reduce the land degradation.

Achieving zero net land degradation will not be straitforward. However, the variable climate patterns, and the several risks posed by the climate change suggested that there is the need to act now in order to stop land degradation, especially in area where people are strictly dependent on natural resources and soil productivity. The livelihoods of rural communities are in jeopardy due to population pressure, land shortage, climate change, and improper land management. Only intense restoration programs that take into account also socio-economic aspects (such as market, rural credit, and crop prices, etc.), and development policies (e.g. alternative livelihoods strategies) could reverse land degradation trends, and subsequentely increase human well-being.

According to this study, it is possible to recorgnise that land degradation is a wicked problem, where socio-economic and political issues play a crucial role; therefore, this BBN approach could also be integrated with other variables to include other important aspects (e.g. socio-economic and political aspects). This is possible due to the flexibility of the BBN tools, that facilitate the integration of new data and information when they come available, as well as the combination of variables from different disciplines (e.g. bio-physical and socio-economic variables), and domains (e.g. qualitative data from stakeholders involvement and participatory approaches, and quatitative data from modelling and mapping approaches) (Aalders 2008; Pollino and Henderson 2010; Celio et al. 2014; Gonzalez-Redin et al. 2016).

6. CONCLUSIONS

A comprehensive assessment of the land degradation risk is needed in order to facilitate decision-making processes. The integration of spatial data in the BBN modelling represents an efficient means to inform stakeholders and decision-makers due to the BBN ability of making complex information promptly visible, through a spatial representation of the issue considered. The novel approach presented here integrated spatial modelling results with other knowledges (e.g. local knowledge, and knowledge derived from literature review), making complex information more accessible through a synthetic land degradation risk assessment.

The study presented proved to be a useful modelling approach for identifying and targeting areas for restoration purposes. Moreover, the integration of scenarios in the BBN modelling highlighted the importance of land use change in affecting the environment, and in determining the seriousness of the issue.

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CHAPTER 6

General Discussion

1. GENERAL DISCUSSION

This PhD project focused on the assessment of land degradation risk at a local level, integrating different disciplines and different levels of knowledge. The approach presented in this PhD thesis could represent an effective means for advocating and informing decision-making processes, that need detailed and accurate assessments for targeting priority areas and interventions, and for achieving inclusive development and economic growth strategies.

1.1. Executive summary

The different steps of the PhD project assessed and implemented valuable approaches and methods to gain a complete appraisal and knowhow of the land degradation problem in the study area.

Three ecosystem services were modelled: soil erosion and retention, nitrogen retention and export (Chapter 2), and carbon storage and sequestration (Chapter 3). In both Chapters, one of the principal aims was to address land degradation risk through the lens of key ecosystem services. Furthermore, thanks to the use of two different sets of data (i.e. "global dataset" and "hybrid dataset"), it was possible to derive the limitations, and the advantages of using data from global coverage datasets to model at a local scale. The results showed that caution is needed when modelling at a local scale, and that modellers cannot rely on global coverage data to derive reliable absolute ecosystem services estimates. However, data from global coverage data can be used for estimating relative ecosystem services values at sub-catchment level.

Another important part of this PhD work, presented in Chapter 4, was to develop a participatory approach to gain local perspective on the land degradation risk, by involving the communities of the three *kebeles*: Andegna Choroko, Layignaw Arsho, and Asore. The participatory approach proved to be an effective means to elicit local perspective and knowledge from the participation of local farmers, as well as experts of the Halaba Agricultural Office. The main objective of this study was to address land degradation causes and consequences, taking into account several environmental and socio-economic aspects. The results showed the presence of a combination of complex interactions between land degradation, environmental and climatic issues (e.g. soil erosion, deforestation, flooding and drought), and socio-economic factors (e.g. land tenure system, market access, population growth and poverty).

The last step of this PhD project was to develop a modelling approach to facilitate the integration of transdisciplinary knowledges in one framework, for inferring land degradation risk, taking into account the information and knowledge gathered during the participatory approach, the literature review, and through the ecosystem services modelling. Therefore, in Chapter 5, Bayesian Belief Network methods were integrated with GIS (Geographical Information System) modelling to derive a spatial explicit appraisal of land degradation risk.

The principal aim of this study was to map land degradation risk in different scenarios of land use cover change. The results showed that certain areas might by highly vulnerable to high degradation if restoration interventions are not implemented. Moreover, this study showed that BBN modelling, when integrated with GIS tools, represents an efficient means for spatially assessing land degradation accounting for biophysical as well as social factors.

1.2. Lessons learnt

Since land degradation lowers the capacity of the ecosystem to provide goods and services (MEA 2005), an effective way to assess land degradation risk is to quantify certain ecosystem services (Chabrillat 2006; Kairis et al. 2014; Tarrasón et al. 2016).

The three ecosystem services (ESS) modelling results helped quantifying the severity of land degradation at the local level. High soil erosion rates were identified. Nitrogen retention was low, also because of low manure and fertiliser application rate. Furthermore, also the estimates of carbon storage and sequestration were low. These ESS assessments could represent effective means for selecting and targeting highly degraded areas to advocate restoration programs. They could also help identifying areas where the current land management proved to be a good solution for reducing land degradation risk. This was the case of the hilly north-western area, where implementation of conservation measures (e.g. terraces), and agroforestry practices, together with higher vegetation cover, likely helped reducing the adversely impacts of land degradation, by reducing soil erosion, enhancing carbon sequestration and nutrient retention.

The approach used in the ecosystem services modelling enabled to identify the limitations of using global datasets when mapping at a small and local scale. In Chapter 2 and Chapter 3, the ESS were modelled using either data only from global coverage datasets (such as MODIS, ISRIC, WorldClim), or a combination of soil properties data from a local survey, a supervised land use classification and some data from global coverage datasets (e.g. climatic data, evapotranspiration amount). The comparison between the two sets of ESS modelling results (i.e. “global” and “hybrid” ESS modelling results) showed that care is needed when using global datasets to assess land degradation, for informing local decision-making processes.

However, the carbon storage and sequestration comparison showed that to determine the relative ranking amount of carbon stocks at sub-catchments level, an assessment that uses global data could be sufficient and effective. Nonetheless, to obtain more accurate and reliable assessments, the ESS modelling studies found that there is the need to use local data, as well as better land use cover map classification.

The difficulty in retrieving high resolution satellite images with low or no clouds cover often constitutes a problem when assessing environmental factors in Ethiopia. In fact, the ESS modelling studies agreed with Liu et al. (2008) and Bai et al. (2013) that found how lack of high resolution spatial data represents a considerable constraint for achieving reliable assessments, and accurate quantification of different ecosystem services. However, this will likely improve with the new Copernicus fleet of sensors (e.g. Sentinel 1 and Sentinel 2) fully deployed by the European Space Agency (ESA) (Drusch et al. 2012; Torres et al. 2012). Moreover, the spatial ecosystem services modelling proved to be challenging because of lack of an accurate and detailed land use cover map, as well as lack of satellite images for the vegetative season, due to the high cloud cover that characterised the rainy seasons (Biazin and Sterk 2013). Therefore, distinguishing between different land use cover proved to be challenging, because the satellite images used for the classification were mainly from the dry season, and because of the high heterogeneity of the Ethiopian landscape, which is characterised by small patches of different land use cover derived from decades of small holdings and subsistence agriculture (Hurni et al. 2015). Thus, after obtaining a supervised classification, an intense manual digitalisation was used for obtaining a high quality land use and cover map. The manual digitalisation was required to distinguish the different land use categories that were confused during the supervised classification, due to similar spectral reflectance characteristic. The manual digitalisation of the supervised classification was necessary because the quality of the land use cover is crucial when mapping ecosystem services that rely on land use classes for the parametrisation of certain variables (e.g. nitrogen export and retention). Furthermore, the land use classification map was also used for determining the carbon stored in the aboveground and belowground biomass.

Spatial explicit and accurate assessments are necessary when trying to inform decision-making processes at a local or national level (Vihervaara et al. 2012; Bagstad et al. 2013; Pandeya et al. 2016). Depending on the objectives and scope of the decision-making processes and strategies, global datasets could either be good enough and suitable for the overarching purpose of the decision-making processes, or be unsuitable due to the lower level of detail and accuracy.

A combination of global available data and data from local survey and supervised land use classification enables a better environmental appraisal, which could identify local spatial patterns that might remain overlooked using low resolution data from global coverage datasets. However, to quantify relative ecosystem services amount and ranking distribution at sub-catchment level, data from global coverage datasets might be sufficient for an informative appraisal of remote areas where local data are scarcer.

The qualitative study presented in Chapter 4 proved to be an effective approach to achieve a comprehensive assessment of land degradation, taking into account local knowledge and perspective. Although the developed participatory approach could not infer all macro-scale aspects likely involved in land degradation exacerbation, and subsequently on sustainable development and economic growth, it was an effective method to achieve a better knowledge of the forces in game at the local scale, and to acknowledge the presence of intricate relationships among socio-economic and environmental factors (Reed et al. 2007; Reed 2008). For capturing also broader and macro-scale factors, national as well as international policies should be considered. However, these aspects are very difficult to capture, and often participatory approaches, which mainly focus on local level assessments, fail to uncover larger scale implications and factors.

Furthermore, the participants' opinions could be limited or driven by the presence, during the discussions and interviews, of people involved in the government. Another constraint that could face a local participatory approach is to target poor participants that are driven by the hope of gaining attention and helps from external parties (Narayan et al. 1999), such as non-governmental organisations (NGOs). For example, the Agricultural Office experts asserted that, during the discussions, farmer households often exacerbate their problems in order to get aids or other helps.

Despite the aforementioned limitations, the method developed in this study enabled to capture relationships and interactions between different aspects (such as climate change, population growth, market development and access, poverty, etc.), and their role in land degradation exacerbation, accounting for local perspective and knowledges (Stringer and Reed 2007).

The findings of the qualitative study showed the presence of a vicious circle between land degradation and poverty. The lack of capacity and of alternative livelihoods' options constrained households' ability and willingness to adopt good land and natural resources management strategies.

In addition, due to population growth, the natural resources exploitation has increased in the recent years. The farmers asserted that now they need to buy grass from neighbour *kebeles*. They also stressed that fuelwood source (bush used also as fence) has been depleted during the last years, and that it is becoming scarcer year by year. Soil fertility depletion was also indicated during the several discussions and interviews. It was found that lack of capacity and lack of awareness obstructed and prevented households from replacing the soil loss fertility, by applying the right amount of fertiliser.

Among the indirect aspects linked to land degradation exacerbation, many participants highlighted the high impact of population growth on the land management. In fact, the study found that population pressure affects several aspects, such as plot size and fragmentation, wealth status, education, crop residues retention, and future land tenure security.

Furthermore, participants recognised that the harming effects of the climate change have increased in the past decades. They indicated that the temperature has raised, and the unpredictability of the rain patterns has increased. In fact, the communities faced in the recent years recurrent droughts as well as floods. This is a serious issue that need to be targeted to developed coping strategies. Hence, the climate change exacerbates land degradation and represents a constraint for a sustainable development and growth (Hurni et al. 2010; Speranza et al. 2010; Reed and Stringer 2015).

However, participants also pointed out that many aspects have improved in the recent years. Extension programs have been developed, health centres have been built, the number of schools has increased, and also the land tenure system has definitely improved as compared to the past years.

Awareness and extension programs were important mechanisms for increasing farmers' willingness to adopt better land management practices and to construct more conservation measures. However, lack of capacity and poor education were indicated as constraints that reduce the effectiveness, as well as the implementation of such measures and practices. Education was reported as a crucial aspect to understand the advices of developer agents on good agricultural practices and conservation measures implementation.

The integration of GIS methods and BBN tools for assessing land degradation risk in different scenarios represents an innovative and novel approach. The approach presented in Chapter 5 provided a “rapid” synthesis of the several knowledges and information acquired using different methods (e.g. ESS modelling, participatory approach, literature review). In particular, in this study, it was possible to obtain the spatial distribution of the land degradation risk in the study area, in four different scenarios, to infer the role of land management and population growth in exacerbating or alleviating land degradation. This synthesis could help identifying areas and/or scenarios likely linked to land degradation exacerbation or alleviation. This approach proved to be an effective means to obtain a spatial explicit assessment of land degradation risk. This is crucial when trying to inform decision-making processes that need accurate assessments for targeting certain areas, as well as for selecting proper measures based on the outcomes of the assessments.

The outcomes of the BBN showed that high population growth and scarce implementation of conservation measures (i.e. scenario 2) are likely associated with increase of land degradation risk in the whole area.

BBN spatial outcomes could inform decision-making processes, because they facilitate the representation of intricate systems (such as socio-agroecosystems) in a visual and spatial explicit framework, which can be accessible also to non-modellers and people without technical skills (Cain 2001; McCann et al. 2006).

1.3. Recommendations and suggested measures

According to the ESS modelling results, the study area appeared highly degraded with high erosion rates (especially in some areas: e.g. riverine areas, steep slope as well as already degraded areas), low carbon storage and sequestration and low nutrient retention. These findings highlighted the need of extensive implementation of restoration practices. In addition, also the spatial BBN modelling confirmed the high risk of land degradation if proper conservation measures are not adopted and implemented at a large scale. For doing so there is the need to act urgently; however, people’s needs could slow down good practices implementation, especially considering the high population pressure in Ethiopia that is estimated to increase in the next decades (FAO and WFP 2010; African Development Bank Group 2017).

This PhD work suggested that there is the need to reverse the land degradation patterns highlighted through the ESS modelling, and through the spatial BBN modelling. However, land restoration interventions and practices cannot solve the problem if not coupled with inclusive development programs (Hurni 1993).

In fact, the findings of this study showed that the land degradation is exacerbated both by poverty and population growth. Hence, land restoration and rehabilitation programs are expected to fail if conservation programs do not consider people short-term and basic needs.

However, the land degradation risk is a complex problem especially in developing countries were promptly and available livelihoods are often the main priority of the majority of the households (UNCCD Secretariat 2013; UNCCD 2014).

Some of the environment restoration practices and measures that could be suggested are:

- Proper manure and fertiliser application, in order to restore the soil fertility, and enhance the crop yield;
- Exclosures establishment to restore already highly degraded land, and increase carbon sequestration;
- Agroforestry practices to increase carbon sequestration, reduce soil erosion, and diversify the livelihoods;
- Multiple cropping system for restoring soil fertility (especially by cropping pulses), and decreasing the vulnerability and exposure to harsh period (e.g. drought);
- Afforestation practices in private land, for increasing the vegetation cover, firewood and construction wood, and for diversifying activities and livelihoods (beehives for honey production, and firewood and thatch grass production) that could be an advantage during dry seasons, and in case of harvest failure;
- Reduced tillage to restore soil water retention capacity and reduce soil erosion;
- Terraces construction in the steep areas that are highly affected by soil erosion.

However, some of the suggested measures present drawbacks and side-effects that could affect their effectiveness, and could generate trade-offs that are difficult to neutralise.

For example, the use of manure, if not careful produced, could cause organic matter depletion in certain and large areas (i.e. where the livestock grazes), whereas its application in the desired areas (farmers' plot) would increase the soil fertility in a small and restricted area. Therefore, manure has to come not by intense removal of vegetation cover and overgrazing in some areas, otherwise the increase in fertility in a certain area would be reached as a result of the overexploitation and degradation of other areas.

Exclosure areas are also linked to several drawbacks. Among them, expropriation of private land, reduction of arable land, increase in available habitats for insects responsible of carrying diseases (such as malaria mosquitos), and for animals that often attack the croplands, causing harvest failures, and sometimes also attack the livestock (such as warthogs, monkeys, porcupines, hyenas). These findings concurred with other studies that stressed how exclosure and restoration areas should be planned with respect of households' livelihoods and short-term needs (Kassa et al. 2009; Byg et al. 2017; Tadesse et al. 2017).

Accordingly, there is the need to introduce compensation measures and schemes (Kassa et al. 2009). This is key to promote conservation and restoration keeping in mind the trade-offs faced by the households, especially the ones that own land at the border with the restoration areas (Byg et al. 2017). Concerning the malaria diffusion, sanitation and health extension programs have already been carried out during the past years, and nets have been distributed. However, it was not possible to estimate the degree of diffusion of mosquitos' nets in the households.

From the knowledge acquired through the ESS modelling and during the participatory approach, it seems that some areas have almost reached a tipping point in terms of land degradation. Probably, intense restoration programs, considering the substantial goals achieved by the previous established exclosures, would be able to foster and achieve soil restoration in many areas. However, reversing land degradation and achieving land restoration would be possible just making large land unavailable for cultivation for several years. This is undoubtedly unfeasible considering the communities' needs. Therefore, there is the need to adopt, together with restoration practices (exclosures and also terraces), better land management (multiple cropping strategies, soil and water conservation measures at plot level, reduced tillage, and fertiliser application). Even though better land management strategies have been increasingly used in the recent years, due to extension and awareness programs, these latter land management practices have been constrained mainly by lack of capacity.

The experts of the Agricultural Office reported the presence of yearly plans for implementing and increasing the restoration areas. They mentioned that, for the 2016, in the Halaba *woreda*, the plan was to convert in exclosure areas 565 ha of communal land, and 140 ha of private farmland. Restoration projects and exclosures establishment should be planned through local participation of the communities involved by the interventions. Local participation might indeed help to support sense of ownerships and higher consent and acceptability among the communities (Reed 2008; Alemayehu et al. 2009; Byg et al. 2017). Furthermore, Tadesse (2001) pointed out that the establishment of private ownership right of exclosure areas to individual farmers would improve their conservation and sustainable use. Ownership rights of exclosure areas could empower households and increase their willingness to preserve them.

Although the implementation of conservation measures and restoration interventions (such as terraces, check dams, exclosures, and recover of gullies) appeared the only solution for reversing the severe land degradation patterns, it is also clear that expropriation of large land is not feasible considering the short-terms needs of the households. Nonetheless, intense restoration programs are key for achieving a better and sustainable development at a long-term scale, but they would probably affect the short-term livelihoods and the crop yield. This is a constraint that is highly important and that must be considered in poor communities, where basic and short-term needs are likely to affect every choice of each household.

It is clear that restoration practices and interventions alone cannot solve the problems of land degradation and scarce development. Besides, land restoration programs alone cannot support the achievement of inclusive and long-lasting economic growth and sustainable development (Byg et al. 2017).

Probably, based on the overall findings of this study, the aforementioned listed measures are straightforward suggestions. Although, due to several socio-economic and political constraints, they are hard to implement even in a small and local scale, such as the study area targeted by this study. Therefore, to be effective, the suggested measures must be associated with socio-economic and political policies that sustain inclusive and sustainable development.

Reduction of population pressure would help decreasing the impacts of people on the environment, and subsequently reducing land degradation. In fact, the area has probably already reached the carrying capacity; no more land is available for cultivation, and procuring enough food for all the members of the family is the only priority of several households. The population growth poses a considerable risk in achieving land degradation reduction as well as inclusive development (Hurni 1993; Desta et al. 2000; Nyssen et al. 2004; Meseret 2016). Thus, there is the need to continue the efforts on family planning that in the recent years has been carried out. Traditional "rules" and beliefs might constitute constraints for the effectiveness of family planning programs. For example, polygamy is still very eradicated at the communities' level. Polygamy was indicated as one of the major causes of population growth. However, family planning could probably be effective only if it is associated with social security schemes. Pension, retirement, and injury insurance schemes could foster a reduction in population pressure and an economic growth, because of the increase of social security (Hohm 1975; Zhang and Zhang 1995). Indeed, having more children is a way of ensuring that you will be provided for in old age. To prevent such "attitude" and mindset, social security must be provided.

Diversification of livelihoods could be promoted by incentivising agroforestry, mono-cropping practices, and by introducing payment for ecosystem services (PES) to support the generation and protection of non-marketed ecosystem services (MEA 2005). Indeed, the PES incentives could stimulate and support afforestation practices together with plantation of fruit trees and with beehives keeping for honey production.

Among the mechanisms that could help in halting land degradation and increasing carbon sequestration, there are the REDD+ (Reducing Emission from Deforestation and Forest Degradation) and the 4 per mille initiatives (Minasny et al. 2017; Gonzalo et al. 2017). As previously mentioned, they could represent good initiatives for reversing land degradation patterns. However, due to the high risk of flooding and drought events that characterised the study area, the promised outputs of a certain mechanism (e.g. soil carbon savings) might be jeopardised. Thus, these mechanisms could represent risky and uncertain investments that farmers could fail to support, because of the fear of not getting enough money back to repay the investments.

Diversification of livelihoods might support inclusive development and might generate safety against harsh periods (e.g. drought), by creating alternative sources of income and live strategies. However, there is the need to improve the market access. In fact, only with proper market access and good crop prices policies, the farmers will be able to sell surplus and increase their income to support their well-being and generate future economic growth and development (Scherr and Yadav 1996; Barbier 1997; Desta et al. 2000; Hagos et al. 2002; Tefera et al. 2002).

In addition, better land management could be supported by rural credit access. This aspect was indicated as a fundamental factor in promoting conservation measures and better land management, with the application of the right amount of inputs (e.g. fertiliser). Rural credit access and development was indeed reported by several studies as an important factor to promote sustainable land management and adoption of agriculture technologies (The World Bank 2007; Barbier 2012; Wossen et al. 2015).

Furthermore, considering the shortage of land, the scarce land productivity, and the crop yield below the national average (Getnet et al. 2017), it appears clear the need to generate job diversification and alternative opportunities. This would enable the young not to be oblige to continue the farming activities, despite the shrinking plot size, that at each generation becomes smaller and smaller. Job diversification could promote development and growth; however, job diversification might be hindered if it is not associated with land market liberalisation. In fact, the possibility of selling the land would support mobilisation of the people, especially of the educated young that often, after finishing the school, cannot pursue other careers rather that farming activities, because of lack of capacity and lack of job opportunities at their rural *kebeles*. Introduction of selling right would probably foster also better land management. In fact, several farmers were renting in (farmers with small land and enough means for sustaining rental payment or sharing schemes), or renting out (households with urgent need of money, or old farmers without help for farming) part of the land. However, the participants of the interviews and focus group discussions stressed that in rented land the quality of the land management decreases because of the lack of sense of ownership and the inconvenience of investing in conservation and sustainable management (Tefera and Sterk 2010). Therefore, the introduction of land selling right could advocate migration and people mobilisation, as well as better land management, and it could increase young's choices and opportunities.

To summarise, this study showed that there is the need of intense restoration and conservation programs to reverse land degradation patterns. However, when restoration is constrained by socio-economic factors (population growth, priority in fulfilment of households basic needs, scarce and inadequate agricultural development and technologies' innovation), proper policies could promote development of alternative live strategies, support market access and development, encourage out-migration (Scherr 2000; Gerber et al. 2014; Barbier and Hochard 2016). These aspects are crucial to ensure rural development and economic growth.

2. CONCLUSIONS AND FINAL REMARKS

This study highlighted the presence of several aspects and links in affecting land degradation. An ecosystem services approach could represent a valuable means for informing policy and decision-making processes. Land degradation leads to a depletion of ecosystem services, therefore EES modelling represents an effective means for assessing land degradation at a spatial level. However, in order to better understand land degradation risk, participatory approach methods represent important practices to gain local perspectives and knowledges that are crucial to inform decision-makers. Moreover, the integration of different sources of knowledges (e.g. ESS modelling, literature review, and participatory approach), with a transdisciplinary approach, could represent an innovative means to obtain a synthesis of the several aspects considered. This was possible using a combination of

GIS and BBN tools. This approach generated a spatial-explicit land degradation risk assessment in different land use change scenarios.

Furthermore, this study could also be integrated with other information to fill further knowledge gaps. The parametrisation and modelling of other ecosystem services (e.g. other regulating and provisioning ESS), could help in obtaining a more comprehensive appraisal keeping in mind also ESS directly involved in livelihoods security (e.g. water, timber, and grass provision).

In addition, the involvement of other participants and stakeholders in the participatory approach (e.g. politicians, companies' directors) could help inferring also larger and broader-scale aspects (e.g. Ethiopian policies on foreign investments, market and crops prices policies). Indeed, these aspects are likely to remain overlooked with a traditional local participatory approach, despite their importance in affecting people's opportunities, options, and choices at a local level.

Hence, the new knowledges could be integrated in the BBN framework to increase the factors considered, therefore the number of nodes. This aspect is possible due to the high flexibility of the BBN tool, which enables the integration of new information, as well as the adaptation of the probabilities among variables as soon as new information comes available.

Finally, the integration of different methods, presented in this study, represents a novel approach that could be considered for obtaining reliable assessments in remote area and in developing countries, considering also poor people's voices, which are often not properly recognised and valued.

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SUPPLEMENTARY MATERIALS

APPENDIX A

1. DATA SOURCES

1.1. Remote Sensing data

1.1.1 Landsat

Eight Landsat 8 scenes (USGS) of 30 metres resolution were selected during the dry seasons of 2013, 2014 and 2015. The scenes during the other seasons had a too high cloud cover to be used. The scenes were downloaded from the U.S. Geological Survey dataset at the following link: *https://earthexplorer.usgs.gov/*

These satellite images were used to calculate the NDVI (Normalised Difference Vegetation Index) using the following equation:

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)} \qquad (A.1)$$

where:

NDVI = normalised difference vegetation index

NIR = reflectance in the near-infrared

RED = reflectance in the red

We used the max value of NDVI obtained from the eight different scenes Landsat.

The NDWI was calculated as (Gao 1996):

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR} \qquad (A.2)$$

where:

NIR = Near InfraRed

SWIR = Short Wave InfraRed

1.1.2. MODIS

The average annual potential evapotranspiration for 2000-2013 time period was download from the MODIS database:

MOD16A3, *http://files.ntsg.umt.edu/data/NTSG_Products/MOD16/*.

1.1.3. Sentinel 1

The Sentinel-1 (S1) mission provides data from a dual-polarisation C-band Synthetic Aperture Radar (SAR) instrument. This includes the S1 Ground Range Detected (GRD) scenes, processed using the Sentinel-1 Toolbox to generate a calibrated, ortho-corrected product. Each scene was pre-processed with Sentinel-1 Toolbox using the following steps: Thermal noise removal, Radiometric calibration, Terrain correction using SRTM 30. The final terrain corrected values were converted to decibels via log scaling $log_{value} = 10 \times log_{10}(value)$ and quantized to 16-bits. The data were pre-processed, prepared, mosaicked and downloaded from Google Earth Engine (Gorelick et al. 2017). The median of the images available between June 2015 and May 2016 was calculated for VV and VH polarisation. No further transformations were applied.

1.1.4. Sentinel 2

Sentinel-2 (S2) is a wide-swath, high-resolution, multi-spectral imaging mission supporting Copernicus Land Monitoring studies, including the monitoring of vegetation, soil and water cover, as well as observation of inland waterways and coastal areas. Each band represents TOA reflectance scaled by 10000. The data were mosaicked and downloaded from Google Earth Engine (Gorelick et al. 2017). The same indices calculated with Landsat were calculated with corresponding bands from S2.

1.2. SRTM

The digital elevation model (DEM) map of 30 m of resolution derived from the Shuttle Radar Topography Mission (SRTM) was downloaded from the USGS (U.S. Geological Survey) database (*https://earthexplorer.usgs.gov/*).

1.3. WorldClim

Monthly rainfall amount (mm) for 1970-2000 time period were downloaded from the WorldClim global dataset (*http://www.worldclim.org/*) (Fick and Hijmans 2017). The average annual precipitation in mm was calculated as the sum of each monthly rainfall amount.

1.4. Global soil data

Global soil data were downloaded from the ISRIC – World Soil Information dataset SoilGrids (*ftp://ftp.soilgrids.org/data/recent/*), a global collection of soil properties maps at 250 m spatial resolutions (Hengl et al. 2017).

1.5. Global land use

The FAO Land Cover of Ethiopia map was derived from the Global Land Cover Network (GLNC), a global cover archive of 300 m spatial resolution (Arino et al. 2008; FAO 2009; Arino et al. 2010). The GlobCover has been reprocessed to generate database at national extent, with few adaptations to the legend.

We used the Ethiopian version downloaded from the FAO GeoNetwork database (*http://www.fao.org/geonetwork/srv/en/main.home*). Fig. A.1 shows the global land use of the study area.

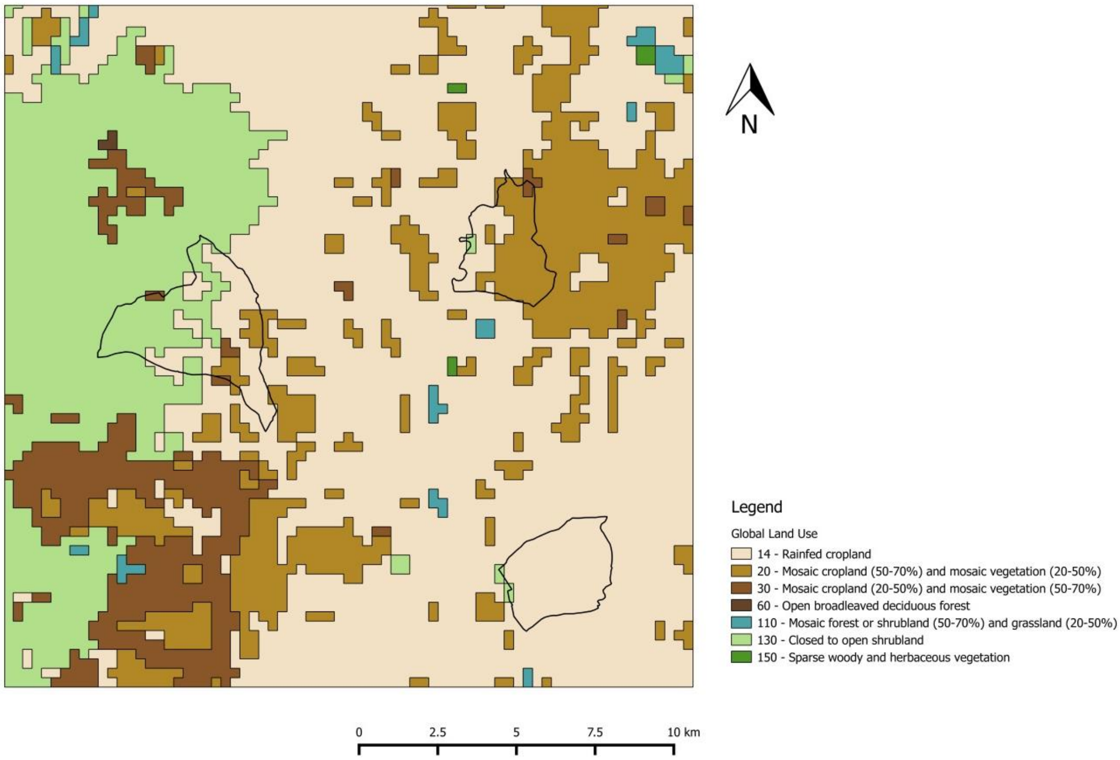

Figure A.1. Global land use.

2. Data preparation and details on methods

2.1. Local land use

The local land use dataset was derived using a two-step supervised classification. In the first step, 670 points were selected and classified using local expertise. A first approximation of the local land use classification was obtained using a classification and regression trees approach (namely RandomForest; Breiman 2001) with the points and a number of covariates, derived from elevation and Landsat datasets (see previous section of this Appendix for further details). The derived land use classification was subsequently verified and manually modified using Google Earth® images as background. Several polygons categories were changed base on local knowledge of the area to differentiate between land use classes that in the automated classification were confused (e.g. degraded land, restoration land and croplands) due to their similar reflectance spectrum. Polygons characterised by mixed semi-natural vegetation and agroforestry were differentiate from the forested areas. Areas characterised by small settlements and cropland alongside them were also individuated and differentiated from Halaba urban area or farmland areas. Fig. A.2 shows the final local land use map.

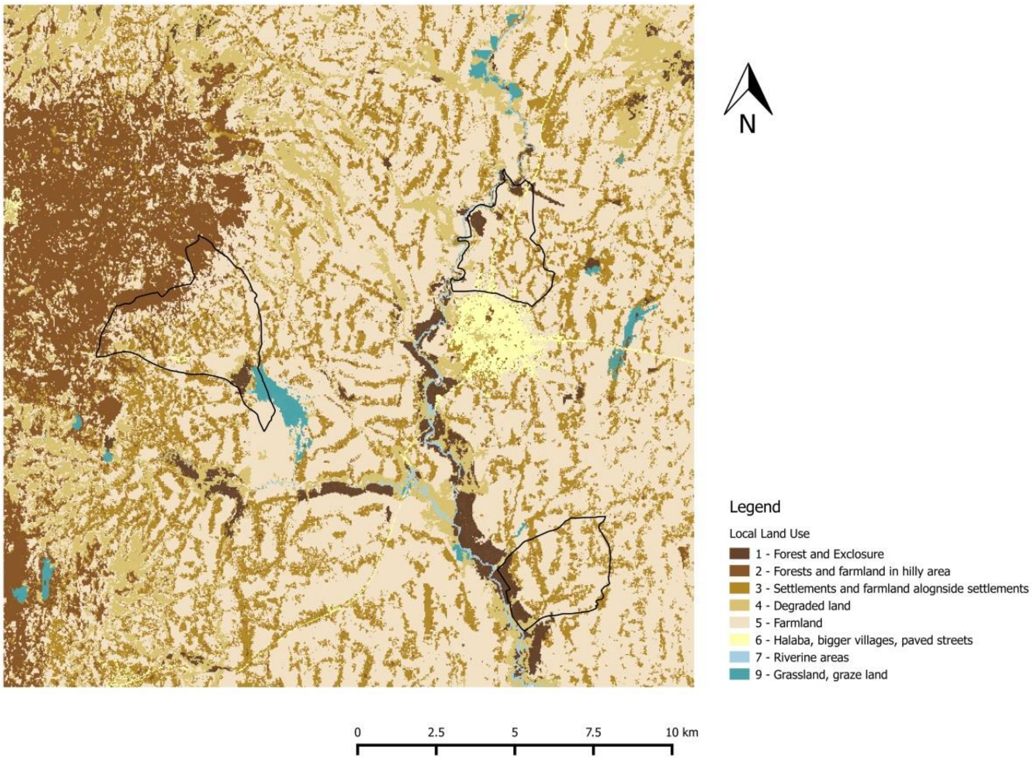

Figure A.2. Local land use classification.

2.2. Morphological features

The SRTM (Shuttle Radar Topography Mission) digital elevation map (DEM) downloaded from the USGS (U.S. Geological Survey) database (*https://earthexplorer.usgs.gov/*) was used for calculating the following parameters:

- Slope: slope value in degrees of inclination from the horizontal (Horn 1981).
- slope length (LS) factor: the LS factor was calculated based on Weltz et al. (1987) that uses the DEM as input.
- Sub-catchments layer: Catchments were obtained using the method of multiple flow direction (MFD) with a threshold of 4000 to have areas with a meaningful size (see Fig. A.3). In the MDF method (Ehlschlaeger 1989; Quinn et al. 1991; Holmgren 1994) the water flow is distributed to all neighbouring

cells with lower elevation, using slope towards neighbouring cells as a weighing factor for proportional distribution.

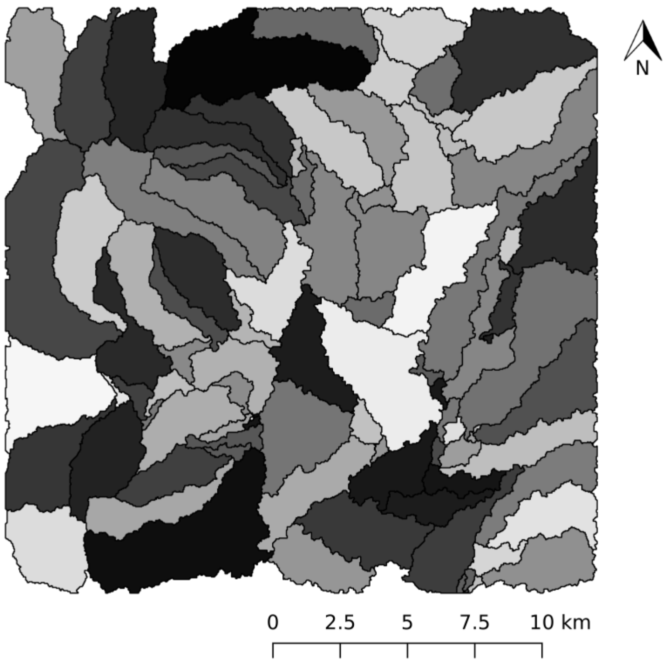

Figure A.3. Map showing the distribution of the sub-catchments.

2.3. Global soil data

2.3.1. SOC%, Soil texture, AWC

The data for the first 20 cm of ISRIC soil organic carbon percentage ($SOC_{\%}$), soil texture (sand, silt and clay) and plant available water (AWC) were obtained using the trapezoidal formula as indicated by Hengl et al. (2017):

$$\frac{1}{b-a}\int_a^b f(x)dx \approx \frac{1}{(b-a)}\frac{1}{2}\sum_{k=1}^{N-1}(x_{k+1}-x_k)(f(x_k)+f(x_{k+1})) \quad \text{(A.3)}$$

where:

N = number of depths considered;

x_k = $k_{\text{-}th}$ depth;

$f(x_k)$ = value of the target variable (i.e., plant available water) at depth x_k.

From the $SOC_{\%}$ we calculated the soil organic matter (OM) percentage as (Van Bemmelen 1890):

$$OM_{\%} = SOC_{\%} \times 1.72 \quad \text{(A.4)}$$

SOC and OM are defined as the amount of soil organic carbon and soil organic matter in percentage. Soil texture is defined as average amount of sand silt and clay in percentage.

Plant available water (AWC) is defined as the difference between water content at field capacity (FC) and water content at permanent wilting point (WP) (Kirkham 2014). In this case it was derived with a FC of pF 2.3 (Hengl et al. 2017).

2.4. Local soil properties

In this study the following local data variables were obtained for 20 cm of soil depths. The samples were analysed following standard international ISO methods:

- Organic matter content (%): organic matter content in percent determined by Walkley-Black oxidation and spectrophotometric analysis (Walkley and Black 1943);
- Bulk density (g/cm^3): dry bulk density of soil in grams per cubic centimetre, calculated as weight of soil divided by volume of core;
- Soil texture (sand, silt and clay content in %): fraction of sample defined as percentage of particles between 2 mm and 50 µm (sand), between 50 µm and 2 µm (silt), and smaller than 2 µm (clay) determined by laser diffraction;
- Soil water at field capacity (FC) and at wilting point (WP) (%): water content held by soil at a potential of 33 kPa (FC) and of 1500 kPa (WP) obtained using a pressure plate.

2.5. Local soil properties maps

Local soil properties maps were obtained through an interpolation process.

An extension of the scorpan-kriging approach (McBratney et al. 2003), i.e. hybrid geostatistical Generalized Additive Models (GAM; Wood 2006), combining GAM with kriging (Poggio and Gimona 2014; Poggio and Gimona 2017) was used following this steps:

1) the fitting of a GAM to estimate the trend of the variable with related covariates;

2) kriging of GAM residuals as spatial component to account for local details. A variogram (Cressie 1993) was fitted for the residuals. Exponential and spherical models (Goovaerts 1997; Deutsch and Journel 1998) were tested and the model providing the lowest AIC was retained. Anisotropy was also taken into account and the variograms were fitted accounting for the principal anisotropy axes (Goovaerts 1997).

The prediction grid had a resolution of 25 × 25 m for the first 20 cm of depth.

The covariates used were: i) derived geomorphological features and ii) indices derived from remote sensing layers. In Table A.1 are reported the predicted soil property data, and the number of points and the covariates used for their prediction.

Table A.1. List of the soil properties predicted and the covariates and points used in the prediction.

<table>
<tr><th>Predicted soil properties</th><th>Covariates used in the final model</th><th>Number of points available</th></tr>
<tr><td>Organic matter (%)</td><td>- NDWI
- elevation
- coordinates</td><td rowspan="4">354</td></tr>
<tr><td>K factor (see Section 3.2.2)</td><td>- slope
- NDVI
- NDWI
- elevation
- coordinates</td></tr>
<tr><td>Soil water content at field capacity</td><td rowspan="2">- NDVI
- elevation
- coordinates</td></tr>
<tr><td>Soil water content at wilting point</td></tr>
</table>

The plant available water content can be defined as the difference between the soil water content at field capacity (FC) and at wilting point (WP). FC and WP data represent the water content held by soil at a potential of 33 kPa and of 1500 kPa respectively (Kirkham 2014).

The plant available water content (AWC) was then calculated as the difference between WP and FC.

2.6. Support practice factor (P factor)

The P factor of the erosion equation (USLE and RUSLE) is the ratio of soil loss with a support practice like contouring, strip-cropping, or terracing to the corresponding loss with up-and-down-slope colture and straight-row farming as indicated by Wischmeier and Smith (1978). The P factor is a dimensionless factor that varies between 1 in the absence of soil and water conservation (SWC) measures that positively reduce soil loss, and 0 in the case of the presence of SWC measures capable of reducing the average soil loss to null.

The P factor was set to 1 for the global modelling. For the hybrid modelling several polygons were digitalised base on a good expert knowledge of the area and using Google Earth® images as background. Two different categories of soil and water conservation (SWC) measures were identified: i) restoration areas with terraces and afforestation practices, and ii) cultivation areas in terraces.

Values of 0.5 and 0.6 were assigned at the restoration areas and at the terraced cultivation areas, respectively, based on P factor values reported in other studies for

Ethiopia (Hurni 1985; Eweg et al. 1998; Haregeweyn et al. 2013). The obtained map is shown in Fig. A.4.

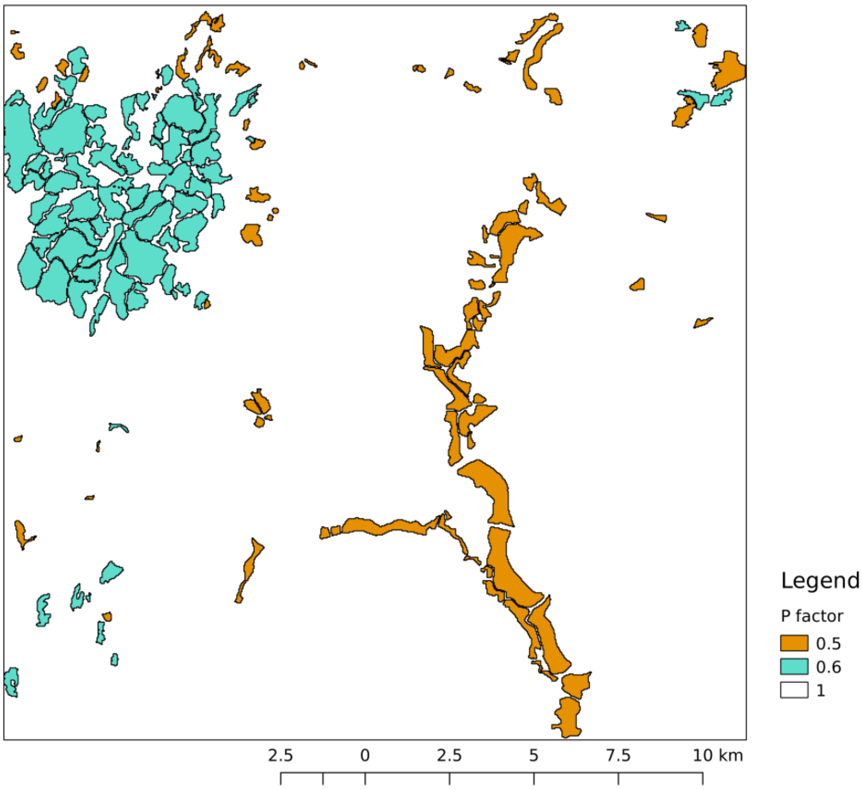

Figure A.4. Map of P factor for the hybrid modelling.

3. InVEST tool

InVEST is a widely applied tool to model and map several ecosystem services (terrestrial, freshwater, and marine), and to explore how changes in ecosystems could lead to changes in goods and services. It is developed under the Natural Capital Project (*https://www.naturalcapitalproject.org/invest/*). It is a useful tool to inform decision-making processes. Furthermore, InVEST can quantify changes in the services and benefits delivering by modelling scenarios of changes to explore the consequences of expected changes on natural resources (Sharp et al. 2015).

In this study, we model the nitrogen retention and export using the model developed in InVEST 3.2.0 (Nutrient Retention: Water Purification). It estimates the vegetation and soil contribution in purifying water through the removal of nutrient pollutants from runoff. The model calculates the amount of nutrient retained on every pixel and sums nutrient export and retention per watershed. Moreover, InVEST model also calculate the economic value that nutrient retention provides through avoided treatment costs (Sharp et al. 2015).

The model is limited to an annual average bases, and does not address chemical or biological interactions besides filtration by terrestrial vegetation. Moreover, it assumes that non-point sources of water pollution result from export that can be mitigated by vegetation serving as intercepting filters (Sharp et al. 2015).

The model runs in two main phases:

- It calculates annual average runoff from each parcel;
- It determines the quantity of nutrient retained by each parcel on the landscape (Sharp et al. 2015).

The amount of downstream pixel retention can be calculated as surface runoff moves the nutrients toward the stream, based on slope and on the land cover type's ability to retain the modelled nutrient. Thus, the model calculates how much nutrient reaches the stream (Sharp et al. 2015) (for further technical details see the InVEST 3.2.0 Documentation at: *https://www.naturalcapitalproject.org/invest/*).

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APPENDIX B

1. THE PARTICIPATORY APPROACH – METHODS

1.1 What?

What are the key objectives to be addressed and to be accomplished through the participatory approach?

1. Try to infer the main drivers and impacts of land degradation in the three *kebeles* considered.
   a) What are the main activities and issues that affect and exacerbate land degradation in the three *kebeles*? What are the different **drivers of land degradation**? Try to assess three different categories of drivers:
   - physical and climatic;
   - social, economic and political;
   - management activities (for cropland and graze land).

   b) What are the major **consequences of land degradation**?

   c) Are there some solutions or measures to reduce the land degradation? Highlight the types of **conservation measures** that could help in preventing land degradation in area not degraded yet.

   d) What are the main livelihoods or ecosystem services (goods and services) that are affected by land degradation? How does land degradation affect poverty exacerbation? Who is mostly affected by land degradation?
2. Evaluate the causes of population growth. Try to understand the causes of the current population growth trends.
3. Try to construct plausible and realistic scenarios.
4. Analyse the land tenure system.
5. Highlight and assess the young's hopes and ambitions.

1.2. Who?

Who do I want to involve? Try to assess two different levels of knowledge. Assess the same objectives with different participants: communities (community and farmers' local knowledge), and agricultural office experts (institutional and political knowledge).

1.3. How?

Depending on the objectives how many interviews, focus group discussions (FGDs) or small group interviews I need to establish and to accomplish?

Privilege small groups (3-5 people). Different groups depending on the gender (women and men) and on the wealth status (rich, medium, poor). For delicate issue (land tenure) do single interviews and not FGD.

1.3.1. General recommendations

Try to divide the focus groups' attendees in order to include and differentiate the households per poverty level according to the selected 75 households, derived from previous wealth status exercise (Byg et al. 2017). Try to address the differences between the different level of poverty organising 2 different FGDs with the participants separated depending on the poverty stratifications (one FGD with medium and poor households and one FGD with poor households). Try to involve the householders already individuate during the soil sampling survey (Black et al. 2015) in order to have information that could be supported also by field data.

Make sure that all the attendees are involved in the information sharing and to be neutral as much as possible, avoiding to intervene in the discussion and to influence participants' feedbacks (Chambers 1994; Mosse 2001; Lynam 2001; Kienberger 2008).

2. WORKING WITH THE COMMUNITIES

2.1. Objective 1: Causes and consequences of land degradation – Conservation measures – Livelihoods and ecosystem services

1.a - What are the main aspects that affect land degradation?

How does the physical asset exacerbate land degradation? How do the socio-economic and political assets exacerbate land degradation? Finally, what are the main management activities that exacerbate land degradation (try to assess two different type of activities: cropping and grazing)?

At what level do these aspects affect land degradation and soil erosion? Can these aspects lead to different types of agriculture (subsistence, intensive, extensive) and to low productivity/low crop yield? If yes, explain why.

1.b - What are the main consequences of land degradation? Is poverty one of the effect of land degradation?

1.c - Are there some solutions or measures that could help reducing land degradation and alleviating poverty?

1.d - Highlight the livelihoods and the ecosystem services affected by land degradation.

2.1.1. Methods

2 Small groups interviews/focus group discussions (5-7 people) (Rietbergen-McCracken and Narayan 1998; Slocum 2003; Bradley and Schneider 2004; de Zeeuw and Wilbers 2004; Jallow and Malik 2005; The World Bank 2007); rich and medium group, and poor group, divided also per gender (4 groups in total per *kebele*).

Time: approx. 5 hours for each focus group (per 4 groups).

Equipment: Audio recorder, notebook and pens.

2.1.2. Objective 1.a, 1.b: Causes and consequences of land degradation

- How does the climate affect the land degradation?
- Can you identify some climate patterns of the last years? If yes, how do you think they affect and will affect the landscape?
- What are the consequences of the declining size of the plot in the fertility of the plot? Furthermore, is the fragmentation (cropland spreads in different and several plots) an issue for the fertility of the plot?
- What agriculture types (subsistence, extensive, intensive) you can identify and highlight in your *kebele*? Explain the different types and outline the more productive type.
- Explain the pros and cons of the agriculture types identified.
- Are there constraints in using the more efficient agriculture type?
- What is the role of the policy and government in affecting land management?
- Does the government have a key role in affecting the agriculture type (intensive, subsistence)?
- What is the role of khat in different aspects, such as agricultural labour, farm activities, social aspects (get credit, sell products, socialisation) (pros and cons)?
- In complex what is the role of khat in poverty exacerbation/alleviation?
- How is the irrigation system in your *kebele*? Do you have an irrigation system? What role has the irrigation system in the cropland management?
- Does the availability of irrigation system depend on the wealth status?
- Are there some measures adopted by the government to enhance and improve the irrigation system?
- Do you think that education has a crucial role in enhancing the crop yield? Or it is not important? Explain why.
- What is the role of education in poverty exacerbation/alleviation or vice versa?
- Does the government have a crucial role in promoting and encouraging the spreading of education?
- Are there constrains in promoting education?
- How do the total income and the wealth status affect the land management?

- Do you think that the market access is important in affecting the land management?
- And the credit access, does it affect the land management?
- Is poverty one of the effects of land degradation? If yes, explain how poverty can affect land degradation?
- Do you have some solutions to alleviate poverty?
- Who is mostly affected by land degradation? Are some households more resilient to land degradation than others? What are the aspects that matter?
- Does the wealth status matter in adapting to climate changes?
- Are there some aspects connected to religion and beliefs that can be involved in land degradation exacerbation? Do these aspects affect land degradation? Explain.

2.1.3. Objective 1.c: Conservation measures

What is the role of conservation measures (also exclosures) in land degradation reduction or poverty exacerbation/alleviation? How could the land degradation be avoided in areas not degraded yet?

Do you find that conservation measures (such as exclosures) have some benefits on the ecosystem services (e.g. soil protection, soil erosion)? Are these conservation measures useful for reducing land degradation? Are there some side effects and drawbacks in the utilisation of such measures?

This focus group could help finding the variables that should be kept in consideration in order to reduce land degradation and then to alleviate poverty.

- Do you identify several types of land degradation? If yes, explain them and their causes.
- What types of conservation measures would you suggest in order to reduce land degradation and soil erosion?
- And even more important, what conservation measures could be useful in order to avoid land degradation in areas not degraded yet?
- Where do you think that the conservation measures are more effective? What does determine effectiveness?
- Do you use some measures to increment the yield and harvest?
- If yes, do you notice some improvements? Explain them; how can you define the improvements?
- Do you use some measure to protect the soil?
- If yes, do you notice some improvements? How can you define them?
- In your opinion and with your experience, how important is the tilling or ploughing in maintaining the soil fertility and so in increasing the crop yield?
- Do you think that tillage could exacerbate soil erosion?

- Can you outline some possible drawbacks and side effects of using conservation measures (exclosure, terraces, etc.)?
- What are the constraints in conservation measures utilisation?
- Do the government and its policies play a crucial role in facilitating the spreading and utilisation of conservation measures?
- Does the government incentivise some measures in order to alleviate land degradation? If yes, how it does that? Are these measures useful in order to reduce land degradation? List them and explain.
- Does the wealth status matter in conservation measures utilisation? Do the poorest farmers use these measures? If yes, explain if there are some differences of use, and conservation measures linked to the wealth status. If no, explain why.
- Does education play an important role in their utilisation?
- Does the credit access have an important role in conservation measures utilisation?
- Have the conservation measures changed during the last years? If yes, have these changes improved the land and soil protection?
- What is the role of fertiliser in the crop yield?
- What are the constraints in adopting fertiliser in your plot?

2.1.4. Objective 1.d: Livelihoods and ecosystem benefits

What are the main livelihoods and ecosystem services (ESS) (goods and services) that are affected by land degradation? Therefore, how land degradation affects poverty exacerbation? How do you cope with land degradation and shortage of crucial livelihoods (deforestation, exploitation of fragile land, overgrazing)? Furthermore, try to focus your attention also on hard periods (drought, flood); how the community's livelihoods change depending on climate?

- What are the materials, goods, livelihoods/ESS that you take from the ecosystem (timber, clean water, fuel, construction material, other source of food apart from cropland yield)? And where do you take these goods?
- How does land degradation affect the utilisation of natural resources and ecosystem services (water, timber, fuel, yield/food, grass and livestock forage, etc.)?
- Do you think that crop yield is affected by land degradation? At what level? Can you cope with decreasing of crop yield using fertilisers? Are some farmers more resilient since they have more access to fertilisers?
- Concerning hard periods (e.g. droughts, floods. Explain them.), how do you cope with them? Do you change livelihoods? Do you think to migrate?
- How do you cope with land degradation and shortage of crucial livelihoods (deforestation, exploitation of fragile land, overgrazing)?
- Who is mostly affected by shortage of livelihoods caused by land degradation?
- Is the land degradation exacerbated by harsh periods? And how? Explain.

- Do you start changing livelihoods strategies when your land is too degraded to supply a decent and adequate harvest? If yes, what are other sources of livelihoods and more in general income?

2.2. Objective 2: Population growth

Why has the population exponentially grown in the last years?

2.2.1. Methods

2 small group interviews (5-7 people) (Rietbergen-McCracken and Narayan 1998; Slocum 2003; Bradley and Schneider 2004; de Zeeuw and Wilbers 2004; Jallow and Malik 2005; The World Bank 2007): men group, women group.

Time: 1 ½ / 2 hours for each focus group (per 2 groups).

Equipment: Audio recorder, notebook and pens.

Since the population growth has previously been indicated as a huge issue in the three *kebeles* try to assess and highlight what have been the causes of this population growth. Migration, resettlement? Which are the causes of this population trends?

Ask this aspect especially to old men and old women.

Assess the population trends during three key recent period times of the Ethiopian recent history:

- ♦ The imperialist period (Emperor Haile Selassie) – 1916-1974;
- ♦ The military regime period (The Derg) – 1974-1991;
- ♦ After The Derg – Republic, Ethiopian People's Revolutionary Democratic Front (EPRDF) rule – 1991-present.

- Can you highlight some trends of the population density considering three periods (the imperialist period, the Derg period, the period after the Derg)?
    - If yes, explain the reason of these population patterns. Does the policy play a crucial role in these aspects?
- Can you identify some population and demography patterns in the area? Are people organised in groups within the same *kebele*? If yes does this aspect affect land allocation and tenure?
- Is the population currently growing? If yes, for what reasons? Are there some patterns (gender, age) in the population growth in the *kebele*?
- Do the migrations and the resettlements play a role in the population trends and growth?

- Have population movements affected the region? If yes give some examples.
- What role does the population growth play on issue such as deforestation, reduction of vegetation cover, changing in the number of livestock, reduction of fallow utilisation, exploitation of fragile land since there is the need of new land, utilisation of crop residue and manure as fuel or for feeding the livestock.
    - Are there other aspects not already highlighted? List them and explain.
    - Does overpopulation affect health status, wealth status, education feasibility and others aspects such as outbreak of conflicts or diseases?
- Are the plot size, the plot distance from homestead and the property fragmentation affected by population growth? If yes explain. How does it affect these aspects? Do these aspects affect the soil fertility?
- Does the population growth affect the crop yield and productivity? Explain.
- Does it affect also the agricultural type used in the area (e.g. subsistence, intensive, extensive agriculture)? Explain.
- What are other aspects (especially social and economic aspects) that are affected by population growth? List and explain them?
- What is the role of the population growth in affecting the landscape? Does the population growth affect and exacerbate land degradation? If yes explain how.
- How do you cope with land degradation? Are there some farmers more resilient than others? Why? Can you identify coping strategies against land degradation?
- Do you find some solutions to poverty?

2.3. Objective 3: Scenario construction

Try to identify and construct possible and realistic scenarios.

2.3.1. Methods

2 Small groups interviews (5-7 people) (Rietbergen-McCracken and Narayan 1998; Slocum 2003; Bradley and Schneider 2004; de Zeeuw and Wilbers 2004; Jallow and Malik 2005; The World Bank 2007), men group, women group.

Time: approx. 3 hours for each focus group (per 2 groups).

Equipment: audio recorder, notebook and pens, large paper sheets and coloured pens.

Ask participant to “forecast” plausible scenarios given certain situations. How would evolve the land use and land cover if the climate continues like the past years and given certain land management practices and strategies?

Try to evaluate effects on land degradation due to climate change, population growth and changes in the land management. What is the most important aspect between climate, population growth and land management in affecting the land degradation?

In general, for all the scenarios how benefits/dis-benefits will be distributed and livelihoods affected? What would be a “fair” scenario (in terms of environmental justice)?

After giving a short description of the plausible future development ask people to draw four different scenarios according the below described options.

Divide the group in two groups and ask the first group to do the 1st and 4th scenarios and the second group to do the 2nd and the 3rd scenarios.

Scenario 1

- Climate = changes projecting forward the actual patterns of climate changes
- Population = continues growing
- Land management = no changes

If the climate patterns continue like the last decades (increasing drought periods, increasing of temperature), the population continues to grow and the land management type doesn’t change, what type and range of changes would you expected? Will the land degradation increase? Will there be less forested areas? Explain the possible changes in your area and the causes of these changes. Explain where will there be the changes, what will be the areas more damaged? Will there be changes in the land use and land cover classes?

Scenario 2

- Climate = changes projecting forward the actual patterns of climate changes
- Population = no changes (it stabilises)
- Land management = better land management (more conservation measures)

On the other hand, if you manage to apply in the landscape more conservation measures (explain what type of conservation measures and where), where do you think there will be improvement on the reduction of land degradation? What are the aspects that could help the spreading of conservation measures? Try to construct possible and realistic scenario on where the land will be restored. In what area the restoration is feasible and realistic? Will there be changes in the land use and land cover classes? What are the aspects and issues that prevent better restoration of the landscape and ecosystem?

Scenario 3

- Climate = no changes (it stabilises)

- Population = continues growing
- Land management = better land management (more conservation measures)

What could change if the climate stabilises but the population continues growing and the land management improves with the adoption of more conservation measures? Do you think these could be a good scenario in order to decrease the land degradation? Can climate and land management contrast the bad effects of the population growth?

Scenario 4

- Climate = changes projecting forward the actual patterns of climate changes
- Population = continues growing
- Land management = better land management (more conservation measures)

Finally, in the scenario where the climate change continues like the last decades and also the population continues growing but the land management improves with the adoption of more conservation measures, will the land degradation continue with the actual patterns? Is the improvement of the land management sufficient in decreasing or stopping the land degradation, or the population growth and the climate play an important role that cannot be reversed just improving the land management?

2.4. Objective 4: Land tenure system

Analyse the land tenure system. What are the aspects that could ensure a land tenure security? Are there some rules that define the land tenure system?

2.4.1. Methods

Since it is a delicate aspect assesses it through semi-structured single interviews, not focus group discussions.

Furthermore, try to ask indirect question (e.g. what do the other farmers do with their land? NOT: what do you do?)

Time: approx. 1 ½ hour for each interview.

Equipment: Audio recorder, notebook and pens.

- Do you own the land? Explain the land tenure system.

- Explain the changes that happened during the three historical periods (Imperial, Derg, after Derg) on the land property rights.
- What type of property rights do you hold (access, withdrawal, management, exclusion, alienation)?
- Can you identify and highlight different types of land tenure systems that might be operating in the area and the type of property rights associated to them? (Ask these aspects to local experts).
- How do property rights enable and affect people to access, use and alienate the resources and the ecosystem services?
- Which are the rules that regulate the land ownership? (Is the land ownership relatively secure?)
- How land is transfer within families?
- How is the land distributed from parents to children?
- Is there gender equality in the transfer process? More directly what are the women rights over the land and in the transfer process?
- Is the land equally distributed among sons and daughters? If not explain.
- What are the rules that regulate the land transfer?
- Can you rent in or out the land? Explain the process.
- Which are the rules that regulate the leasing?
- How does the leasing from the government work?
- Does the land tenure system affect the land management? And how?
- Do you think that with a different land tenure system you would be more willing to adopt some conservation measures?
- Does the land tenure system affect the land degradation and the poverty? How?
- What are the constraints in achieving a more secure land tenure system?
- Is the deforestation affected by the land tenure system?
- Do you think that the population growth could also depend on the land tenure system? So, does the land tenure system affect the population growth?
- Have there been redistribution during the past and now?
- Can government take your land (land appropriation)?
- Does land tenure security affect marriage status and number of children?

2.5. Objective 5: Young’s hopes and ambition for their future

Assess and highlight the young’s hopes and ambitions.

What would they like to do in their futures?

Do they want to cultivate the land or do they have other ambitions? Do they want to migrate or move to bigger city to find job?

2.5.1. Methods

2 Small groups interviews (5-7 people) (Rietbergen-McCracken and Narayan 1998; Slocum 2003; Bradley and Schneider 2004; de Zeeuw and Wilbers 2004; Jallow and Malik 2005; The World Bank 2007), young men group, young women group.

Time: approx. 2 hours for each focus group (per 2 groups).

Equipment: Audio recorder, notebook and pens.

Ask how old are them.

- In addition to farm activities what other job opportunities exist in your *kebele*?
- Do you want to cultivate the land or do you have other ambitions?
- What are your other ambitions and hopes?
- What would you do when you will finish studying?
- Do your ambitions depend on your wealth status?
- Do you think education is important?
- Do you think education can help enhancing your possibility to succeed in other fields?
- Would you like to migrate or move to bigger city to find job?
- What type of job would you like to do in the future?
- Would you like to continue your studies?
- Is it feasible to you continuing the studies?
- Does the government help the *kebele* families in favouring the education?
- Are there constrains in promoting education?
- Does the wealth ranking matter in the education level?
- What does your family want for your futures?
- Is it important your family opinion in your decision-making process?

3. Working with the Agricultural Office

3.1. Objective 1: Causes and consequences of land degradation

Identify key causes and drivers of land degradation and its consequences (Objective 1.a. and 1.b). Furthermore, try to find possible solutions to reduce land degradation, and thus alleviate poverty (Objective 1.c).

3.1.1. Methods

Use focus group discussion (Rietbergen-McCracken and Narayan 1998; Slocum 2003; Bradley and Schneider 2004; de Zeeuw and Wilbers 2004; Jallow and Malik 2005; The World Bank 2007) or individual interviews (Rietbergen-McCracken and Narayan 1998; WFP 2001; Bradley and Schneider 2004; de Zeeuw and Wilbers 2004) depending on the availability of agricultural office employers.

Time: approx. 4 ½ hours

Equipment: recorder, notebook and pens, laptop

Objective 1.a and 1.b.

Interview someone of the agricultural office. Try to identify the most important drivers as well as consequences of land degradation through structured focus group discussion.

Objective 1.c.

Ask the agricultural officers to find some feasible solutions and measure to break the casual chain of negative consequences of land degradation. Where it is possible to intervene in order to reduce the land degradation and to alleviate poverty? Are the agricultural office's solutions conformed to the farmer's ones?

3.1.2. Objective 1.a, 1.b: Causes and consequences of land degradation

Reply yes or no and then explain!

- Does the population growth affect the utilisation and availability of manure and the use of crop residue for fertility purposes?
- Do farmers use manure for other purposes than fertilisation?
- Do the farmers use manure as fuel instead of as organic fertiliser?
- Do the farmers use crop residues as construction material or fuel?
- Does the plot distance from homestead affect the utilisation of manure?
- Does the plot distance from homestead affect the soil fertility?
- Do the farm size and the security of the land tenure affect the deforestation?
- Does the population growth reduce the fallowing practice?
- Does the population growth affect the livestock pro capita (per person or per household)?

- Does the farm size affect the type of agriculture (intensive, extensive or subsistence)?
- Does the soil type affect the crop choices of the farmers?
- Does the agriculture type (intensive, extensive or subsistence) affect differently the soil fertility, and overall the land degradation?
- Does a drought period exacerbate land degradation and formation of gullies?
- Does the population growth exacerbate the exploitation of fragile land?
- Are the fragile lands less productive?
- Does the ploughing exacerbate the soil erosion?
- Does the market access affect the crop yield?
- Does the market access affect the agricultural type?
- Does the market access affect the crop choices?
- Does the decision of adopt new conservation measures (exclosure, terrace) involve also a participatory decision-making process with the communities?
- Do wild animals interfere with the farmland and affect the crop choices of the farmers?
- Are the farmers usually happy with the mandatory conservation measure such as exclosure (restoration area, terrace)?
- Can the farmers use the timber, the firewood and the grass from the exclosure areas at some point?
- Does the government play a crucial role in conservation measure utilisation?
- Do you think that the land tenure security affects the land management and utilisation of different conservation measures?
- Does the wealth status affect the land management and utilisation of several inputs?
- What are farmers constrains in using conservation measures and fertilisers?
- Does the population growth reduce the grassland and graze land areas?
- Do the market prices affect the crop choices and the type of agriculture?
- Does the wealth status affect the use of fertilisers and other inputs?
- Does the population growth exacerbate the deforestation?
- Do settlement policies affect the population demography in the *woreda*?
- Does the land degradation affect the wealth status and in general the well-being?
- Are the farmers organised in clans?
- Do the clans control the resources?
- Is the access to resources controlled by associations or organisations?
- Does the organisation in clan and the control of the resources affect the well-being?

- In your opinion what are good solutions to reduce the land degradation?
- And what are some solutions to alleviate poverty?

- Where and in what sector should the government act to reduce land degradation and alleviate poverty?
- Does the population growth affect the plot fragmentation?
- Does the land fragmentation affect land degradation?
- Do you think that a more secure land ownership will increase farmers' willingness to adopt conservation measures on their land?
- Can farmers rent their land? Explain the process and the different types of renting.

3.1.3. Objective 1.c: Conservation measures

Cross-check the management activities that could help decreasing land degradation highlighted by the community. Do you think such measures are useful? And could be feasible to encourage the use of such measures?

What are the activities or measures that you are using in order to reduce the high land degradation affecting the region and especially in order to avoid further land degradation in areas not degraded yet?

Use this focus group discussion or interview in order to see if the agricultural office and the farmers agree with the conservation measures that could help reducing land degradation and then poverty.

- Are there any compulsory measures to increment the yield and harvest or to protect the soil? (Do you suggest or oblige farmers to use some measure to increment the yield and harvest or to protect the soil?)
- If yes, do you notice some improvements? How can you define the improvements?
- Are there any conservation measures that help decreasing land degradation and soil erosion?
- What types of conservation measures would you suggest in order to reduce land degradation?
- And even more important, what conservation measures could be useful in order to avoid land degradation in areas not degraded yet?
- Do you find that conservation measures (such as exclosures) have some benefits on the ecosystem services (e.g. soil protection, soil erosion, soil fertility)?
- How can the conservation measures help alleviate land degradation?
- Can you outline some possible drawbacks and side effects of using conservation measures (exclosure) from the political and social point of view?
- What are the constraints in conservation measures utilisation?
- Do the government and its policies play a crucial role in facilitating the conservation measures utilisation?

- Are there some measures that are incentivised by the government? List and explain them.
- Does the wealth rank matter in conservation measures utilisation?
- Do the poorest farmers use these measures? If yes, explain if there are some differences of use and type of conservation measures linked to the wealth status. If no, explain why.
- Does education play an important role in their utilisation?
- I found in the FGDs with the communities that they have highlighted as very important the following measures (…………). Do you think they are important? If, no, why, what are other measures important from your point of view? And if yes, what are you doing (the government and the Agricultural Office and its policies) to facilitate their use?

3.2. Objective 2: Population growth

Why the population has exponentially grown in the last years?

Assess the population trends during three key recent period times on the Ethiopian recent history, as indicate in the FGDs with the communities:

- The imperialist period (Emperor Haile Selassie) – 1916-1974;
- The military regime period (The Derg) – 1974-1991;
- After the Derg – Republic, Ethiopian People's Revolutionary Democratic Front (EPRDF) rule – 1991-present.

3.2.1. Methods

Use focus group discussion (Rietbergen-McCracken and Narayan 1998; Slocum 2003; Bradley and Schneider 2004; de Zeeuw and Wilbers 2004; Jallow and Malik 2005; The World Bank 2007) or individual interviews (Rietbergen-McCracken and Narayan 1998; WFP 2001; Bradley and Schneider 2004; de Zeeuw and Wilbers 2004) depending on the availability of agricultural office employers.

Time: approx. 2 hours.

Equipment: recorder, notebook and pens.

Try in these activities to understand why the population has enormously growth during the last years. Are the farmers' statements confirmed by these findings?

- Highlight some trends of the population density considering three periods (the imperialist period, the Derg period, the period after the Derg)
    - Explain the reason of these population patterns.
    - Does the policy play a crucial role in these aspects?
- Is the population currently growing? If yes, for what reasons?

- Have population movements (migrations/resettlements) affected population and demography trends in the region? If yes, could you please indicate some examples?
- What role does the population growth play on issue such as deforestation, reduction of vegetation cover, changing in the number of livestock, reduction of fallow utilisation, exploitation of fragile land since there is the need of new land, utilisation of crop residue and manure as fuel or for feeding livestock.
    - Are there other aspects that have not been highlighted yet? List them and explain why.
    - Does overpopulation affect health status, wealth status, education feasibility and others aspects such as outbreak of conflicts or diseases?
- Does the population growth affect the farmland system?
- In particular does the population growth affect the farmland asset (fragmentation, size and distance)? And how?
- From your experience, how does the population growth affect the crop yield and productivity?
- Does it affect also the agriculture type (subsistence, intensive, extensive)?
- Are the plot size, the plot distance from homestead and the property fragmentation affected by population growth?
- Therefore, do these aspects affect soil fertility or even land degradation?
- What are the consequences of population growth, concerning the farmland assets, the crop yield, the agriculture type?

3.3. Objective 3: Scenario construction

Try to identify and construct possible and realistic scenarios.

3.3.1. Methods

Small Focus Group Discussions (5-7 people) (Rietbergen-McCracken and Narayan 1998; Slocum 2003; Bradley and Schneider 2004; de Zeeuw and Wilbers 2004; Jallow and Malik 2005; The World Bank 2007).

Time: approx. 2 hours.

Equipment: audio recorder, notebook and pens.

How would evolve the land use and land cover if the climate continues like the past years and given certain land management actions?

Try to evaluate effects on land degradation due to climate change, population growth, and changes in the land management. What is the most important aspect between climate, population growth and land management in affecting the land degradation?

In general, for all the scenarios how benefits/dis-benefits will be distributed and livelihoods affected? What would be a "fair" scenario (in terms of environmental justice)?

After giving a short description of the plausible future development ask participants to describe and forecast plausible four different scenarios according to the below described options.

If there are maps of Halaba *woreda* or of the three *kebeles* ask where they think it is feasible and possible to apply conservation measures in the future? And what type of conservation measures? Are there any plans to construct new conservation measures?

Scenario 1

- Climate = changes projecting forward the actual patterns of climate changes
- Population = continues growing
- Land management = no changes

If the climate patterns continue like the last decades (increasing drought periods, increasing of temperature), the population continues to grow and the land management type doesn't change, what type and range of changes would you expected?

Will the land degradation increase?

Will there be less forested areas?

Explain the possible changes in your area and the causes of these changes.

Explain where there will be the changes, what will be the areas more damaged? There will be changes in the land use and land cover classes?

Scenario 2

- Climate = changes projecting forward the actual patterns of climate changes
- Population = no changes
- Land management = better land management (more conservation measures)

On the other hand, if the population stops growing and if you manage to apply more conservation measures (explain what type of conservation measures and where), what will change on the land cover and land use?

Try to think about possible and realistic scenario where the land will be restored. In what area the restoration is it feasible and realistic?

Where do you think there will be improvement on the reduction of land degradation?

What are the aspects that could help the spreading of conservation measures? And what are the constraints on the spreading of conservation measures?

Will there be changes in the land use and land cover classes?

What are the aspects and issues that prevent better restoration of the landscape and ecosystem?

Scenario 3

- Climate = no changes (it stabilises)
- Population = continues growing
- Land management = better land management (more conservation measures)

What could change if the climate stabilises but the population continues growing and the land management improves with the adoption of more conservation measures?

Do you think these could be a good scenario in order to decrease the land degradation?

Can climate and land management contrast the bad effects of the population growth?

Or does the population growth exacerbate land degradation that cannot be balanced by better land management and better and stable climate?

Scenario 4

- Climate = changes projecting forward the actual patterns of climate changes
- Population = continues growing
- Land management = better land management (more conservation measures)

Finally, in the scenario where the climate change continues like the last decades and also the population continues growing, but the land management improves with the adoption of more conservation measures, will the land degradation continue with the actual patterns?

Is the improvement of the land management sufficient to decrease or stop the land degradation, or the population growth and the climate play an important role that cannot be reversed just improving the land management?

To conclude what is the most important factor in affecting the landscape and in exacerbating the land degradation? Population pressure, land management or climate?

What is the key measure in order to reduce the land degradation? Try to decrease the population pressure or try to apply more conservation measures and restoration practices?

What are possible solutions to land degradation?

3.4. Objective 4: Land tenure system

Analyse the land tenure system taking in consideration the policies and the past and actual rules.

3.4.1. Methods

Use focus group discussion (Rietbergen-McCracken and Narayan 1998; Slocum 2003; Bradley and Schneider 2004; de Zeeuw and Wilbers 2004; Jallow and Malik 2005; The World Bank 2007) or individual interviews (Rietbergen-McCracken and Narayan 1998; WFP 2001; Bradley and Schneider 2004; de Zeeuw and Wilbers 2004) depending on the availability of agricultural office employers.

Time: approx. 2 hours.

Equipment: recorder, notebook and pens.

Does the land tenure type affect the farm size and the fragmentation and finally the land degradation?

After conducting the discussion or interview see if the official rules are the same that have been highlighted by the farmers during the previous single interviews.

- Who does own the land?
- What are the principal rules to control and regulate the land tenure system?
- Explain the changes that have been happened during the 3 historic periods (Imperial period, the Deng period, after Deng period).
- How is land transferred within families?
- How is the land distributed from parents to children?
- Is there gender equality in the transfer process? More directly, what are the women rights over the land and in the transfer process?
- Is the land equally distributed among sons and daughters?
- How does the leasing from government work?
- Can the farmers themselves lease the land to or from other farmers?
- Does the land tenure system affect the size and the possible fragmentation of the plot?

- Do you think that the land tenure system affects the land degradation and the poverty?
- Thus, does the land tenure system affect the deforestation?
- Do you think that strengthen the land tenure ownership could help increasing the farmers' willingness to adopts better land management options and more conservation measures? Explain.
- What are the constraints in achieving a more secure land tenure system?

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APPENDIX C

1. PARTICIPANTS OF THE FOCUS GROUP DISCUSSIONS

The following Tables report the number of participants divided per wealth status (rich, medium, poor) per focus group discussion (FGD), for each objective in the three *kebeles*. The Tables are divided depending on the gender and they also report at which date each FGD was conducted. Objective 4 (land tenure system) is not indicated in the Tables because it was elicited through single interviews; in each *kebele*, 5 men (1 rich, 1 medium, and 3 poor) and 5 women (1 rich, 1 medium, and 3 poor) were interviewed for objective 4.

Table C.1. Andegna Choroko participants at the FGDs per wealth status. R/M: Rich and Medium wealth categories represented. P: Poor wealth category represented.

Male FGD	**Participants (per wealth status)**			**FGD date**
	Rich	**Medium**	**Poor**	
Objective 1 (R/M)	2	5	-	26th April 2016
Objective 1 (P)	-	-	6	28th April 2016
Objective 2	1	2	4	29th April 2016
Objective 3	2	2	5	1st June 2016
Objective 5	1	1	3	28th April 2016
Female FGD	**Participants (per wealth status)**			**FGD date**
	Rich	**Medium**	**Poor**	
Objective 1 (R/M)	3	3	-	27th April 2016
Objective 1 (P)	-	-	5	27th April 2016
Objective 2	1	2	4	29th April 2016
Objective 3	2	2	4	2nd June 2016
Objective 5	1	1	3	28th April 2016

Table C.2. Asore participants at the FGDs per wealth status. R/M: Rich and Medium wealth categories represented. P: Poor wealth category represented.

Male FGD	**Participants (per wealth status)**			**FGD date**
	Rich	**Medium**	**Poor**	
Objective 1 (R/M)	2	4	-	4th May 2016
Objective 1 (P)	-	-	5	5th May 2016
Objective 2	1	1	3	27th May 2016
Objective 3	2	2	4	30th May 2016
Objective 5	1	1	3	5th May 2016
Female FGD	**Participants (per wealth status)**			**FGD date**
	Rich	**Medium**	**Poor**	
Objective 1 (R/M)	2	4	-	4th May 2016
Objective 1 (P)	-	-	7	27th May 2016
Objective 2	1	1	4	26th May 2016
Objective 3	2	2	4	31st May 2016
Objective 5	1	1	3	5th May 2016

Table C.3. Layignaw Arsho participants at the FGDs per wealth status. R/M: Rich and Medium wealth categories represented. P: Poor wealth category represented.

Male FGD	Participants (per wealth status)			FGD date
	Rich	Medium	Poor	
Objective 1 (R/M)	1	4	-	11th May 2016
Objective 1 (P)	-	-	6	12th May 2016
Objective 2	1	3	3	13th May 2016
Objective 3	2	2	4	5th June 2016
Objective 5	1	1	4	11th May 2016
Female FGD	**Participants (per wealth status)**			**FGD date**
	Rich	**Medium**	**Poor**	
Objective 1 (R/M)	2	4	-	11th May 2016
Objective 1 (P)	-	-	7	12th May 2016
Objective 2	1	2	4	13th May 2016
Objective 3	2	2	4	4th June 2016
Objective 5	-	1	6	12th May 2016