THE ECONOMICS OF
LAND DEGRADATION

An economic valuation of sustainable land management through agroforestry in eastern Sudan

Assessing the socio-economic and environmental dimensions of land degradation

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Economics of Land Degradation Initiative: **An economic valuation of sustainable land management through agroforestry in Eastern Sudan**

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Executive summary

Gedaref State was previously known as the food basket of Sudan. Over several decades unsustainable agricultural practices that combined near-monocropping with low nutrient replenishment have led to significant degradation of soils, which are no longer able to sustain farmer livelihoods. This study found that adopting an integrated sustainable land use and forest restoration scenario could reverse the current land degradation trend. The integration of *Acacia senegal* with sorghum, Sudan's primary staple crop, was evaluated as a potential sustainable land management practice. *A. senegal* is a high quality gum arabic producing tree species, traditionally integrated into a crop and fallow system. It has soil nitrogen enhancing properties and international demand for its gum, make it a promising species to integrate in agricultural systems for both environmental and economic health. In parallel, consideration was also given to reforesting hills that have bare and exposed soil, with Luban gum trees such as *Boswellia catering, Boswellia frererana,* and *Boswellia papyrifera*. Currently these hills are not used for productive gains and have no competing land use, thus their reforestation would incur little to no opportunity costs.

The valuation of both proposed integrated sustainable land management and forest restoration scenarios were undertaken using an ex-ante cost benefit analysis. An assessment of the ecosystem services and economic impact of restoration scenarios was carried out using valuation techniques which included a productivity change approach, and replacement and avoided damage cost approaches. The analysis built on high-resolution remote sensing, GIS, and biophysical soil and water assessment tools, allowing for rigourous estimates of the impact of land use change on agricultural yields, groundwater infiltration, water runoff, and carbon sequestration.

The results showed that the net present value returns to society as well as to the individual farmer of intercropping *A. senegal* trees with sorghum crops is significantly higher than that of continuing pure sorghum cultivation over a 25 year time horizon – the length of the productive life of *A. senegal*. At the farmer level, benefits of using an intercropping system outweigh the investment and management costs between three to four years after their establishment. However, favourable estimates of the financial returns from gum arabic offer no guarantee that the farmer will undertake gum production (Barbier 2000). This decision will depend on what returns can be obtained from other crops and the time profile of these returns, as argued in Barbier (1992). Thus, there are a number of fundamental policy initiatives necessary to encourage farmers to transition towards integrating *A. senegal* as part of a sustainable land management system, including security of tenure and access to credit, as well as maintenance of the actual producer price for gum arabic in the long term.

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Acronyms and abbreviations

ArcSwat	(Arc) Soil and water assessment tool
ARMA	Auto-regressive moving-average model
DLDD	Desertification, land degradation and drought
ELD	Economics of Land Degradation (Initiative)
FAO	Food and Agriculture Organisation
FNC	Forest National Corporation
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
IUCN	International Union for conservation of nature
LDN	Land degradation neutrality
NPC	Nominal protection coefficient
NPV	Net present value
NTFP	Non-timber forest product
PV	Present value
SDG	Sudanese pound
SCC	Social cost of carbon
SLM	Sustainable land management
UNCBD	United Nations Convention on Biodiversity
USD	United States Dollar

The economics of land degradation

Sustainable land use is a prerequisite for ensuring future water, food, and energy security. Given the increasing pressure on land from agriculture, forestry, pasture, energy production, and urbanization, urgent action is needed to halt land degradation and restore already-degraded lands. The United Nations Convention to Combat Desertification (UNCCD) was established in 1994 to specifically address desertification. The convention was born as a result of the 1992 Rio Earth Summit, which highlighted climate change, biodiversity loss, and desertification as the greatest challenges facing sustainable development. All three challenges have been attributed to failures in, markets, and policies. The UNCCD's core emphasis is on securing productivity and resilience of land for the well-being of dryland inhabitants, particularly in drought-prone areas. In 2007, a ten year strategy for the convention was adopted with a more explicit goal for its 195 parties, "to forge a global partnership to reverse and prevent desertification/land degradation and to mitigate the effects of drought in affected areas in order to support poverty reduction and environmental sustainability" (UNCCD 2012). The ten year strategy is supported and implemented through key stakeholder partnerships with the aim of mainstreaming sustainable land management (SLM) into decision-making policies and practices.

The UNCCD definition of desertification is land degradation (linked to the loss of productivity of land) in drylands with the exception of hyper arid areas. Although there appears to be a general consensus amongst the parties to the convention that drylands, particularly in Africa, face severe impacts of desertification, land degradation, and drought (DLDD), land degradation is not restricted to drylands. The far-reaching impacts of DLDD affect both livelihoods and ecosystems globally, resulting in the loss of critical ecosystem services ranging from carbon sequestration to losses of fertility and nature conservation. The impacts of DLDD are local but can also be experienced off-site, e.g., when deforestation or poor management of land upstream results in siltation of dams downstream. Impacts of DLDD can be cross-border or even inter-continental, e.g., dust storms where the dust is generated on one continent and travels with prevailing winds and manifests as a dust storm on another continent. The importance of an international convention on desertification becomes strikingly apparent when considering these off-site/cross-boundary impacts that result from DLDD.

In 2013, the 2nd Science Conference of UNCCD was held in Bonn, Germany, to discuss and showcase scientific contributions on the theme "Economic assessment of desertification, sustainable land management, and resilience of arid, semi-arid, and dry sub-humid areas". Throughout the conference, scientists and practitioners presented robust methodologies and evidence to suggest that preventing DLDD can be more cost effective than restoring degraded land. However, there are significant data gaps in the biophysical and economic data and methodologies need to be extensively tested to identify the most efficient methods to collect and compile the data required to fill these gaps. It is evident that the field of economic assessment of SLM is still, emerging but nonetheless an important one.

Central to the debate on the economics of DLDD is the concept of land degradation neutrality (LDN). LDN is a novel idea that was presented in the outcome document from Rio+20 and adopted by UNCCD (UNCCD 2012). Its aim is to secure the productivity of land and natural resources (such as soil) for sustainable development, food security, and poverty eradication. In principle, LDN would translate into avoided degradation of productive land and restoration of already degraded lands to obtain a degradation-neutral outcome. Cost-benefit analyses of SLM is an important approach in strengthening the case for investments in improved land management practices, and is one of the steps necessary to achieve land degradation neutrality.

Promoting SLM and effectively communicating the nexus of benefits derived from SLM has been at the heart of the work of IUCN's Global Drylands Initiative (GDI). GDI is further collaborating with the IUCN Global Economics and Social Science programme (GESSP) that provides technical expertise in the domain of ecosystem service valuation. The SLM nexus highlights the inter-linkages between climate, biodiversity and land, where synergies between the three UN conventions (UNCCD, United Nations Framework Convention on Climate Change [UNFCCC], and the United Nations Convention on Biodiversity [UNCBD]) lie, and where a large portion of IUCN's dryland work is focused. IUCN brings communities and multiple government sectors together to enable more coherent resource planning at the ecosystem level for SLM in the drylands.

IUCN - GDI and GESSP have a history of using economic valuations to demonstrate the benefits of ecosystems and SLM strategies specifically applicable to drylands. To strengthen these existing economic assessments, IUCN has built relationships with other initiatives who share similar goals and objectives, such as the Economics of Land Degradation (ELD) Initiative. The ELD Initiative highlights the potential benefits derived from adopting SLM practices, using quantitative ecosystem valuation studies. Through funds from the ELD Initiative, IUCN carried out an assessment of the economic costs and benefits of SLM and its natural resource governance interventions over several years in Jordan, Mali, and Sudan. These three country studies provided a detailed analysis of the costs and benefits of interventions, information on non-market values of ecosystem services, improved understanding of the value of ecosystem services to local livelihoods, and improved monitoring and evaluation for total ecosystem assessments. The studies demonstrated that long and short term social, economic, and environmental benefits can be derived from adopting SLM practices on a wide scale. These studies also informed the development of policy recommendations which will feed into on-going dialogue with policy- and decision-makers in these regions. Hence, IUCN hopes these studies have provided a fresh insight with innovative methodologies and new data, plus a more comprehensive review of the diversity of ecosystem services that are important in drylands.

01

Introduction

Gedaref State has lost its status as one of the major food production centres in Sudan largely due to unsustainable agricultural practices spanning several decades (Glover and Elsiddig, 2012). According to Ahmed and Sanders (1998), sorghum yields declined by one percent annually from the 1960s to the end of the 1980s. Agricultural practices such as large diffusion of mechanized rainfed agriculture, clear-cutting of vegetative woody biomass for fuelwood and agriculture, and shortening of fallow periods have all contributed to large-scale land degradation (Akhtar et al., 1994; Ahmed and Sanders, 1998; Glover, 2005). The farming system in Gedaref is currently neither fully mechanized nor traditional. Ploughing is mechanised, however, sorghum production is associated with hand weeding, and still extensive. Moreover, replenishment of soil nutrients by organic matter is inadequate and traditional local cultivars are cultivated without the use of any fertilizers to supplement the soil (Ardö and Olsson, 2003). All these elements have and continue to degrade the rich soil, leading to a decline in land productivity[1]. Land degradation has severe impacts on food security in the region increasing the vulnerabilities of the rural poor to climatic and weather uncertainties. Furthermore, land degradation has a significant impact on ecosystem function and provision of ecosystem services, reducing the availability and quality of water, plant, and animal resources for society, primary production, and economic sectors (Salih, 1993).

Unsustainable land management practices in Sudan have been attributed to the lack of local participation in decisions affecting land management (Akhtar et al., 1994; Ahmed and Sanders, 1998) and the lack of appropriate land tenure regimes, both disincentivising land users to invest in SLM practices (Kabubo-Mariara, 2007; Glover and Elsiddig, 2012). For example, a representative sample of household farmers and collaborative reserve farmers[2] in Gedaref (Glover and Elsiddig, 2012) found that more than half of respondents lacked land tenure security due to leaseholds or informal tenure arrangements.

Indiscriminate clear-cutting of forests from large-scale mechanized farming coupled with disincentives to grow trees on farmland has led to a greater dependence by farmers on natural forest reserves for domestic energy and construction from timber (Glover and Elsiddig, 2012). In response to this and more particularly, to relieve pressure on forest reserves, the Forest National Corporation (FNC) introduced a law requiring 10 per cent of total farmland in Gedaref State to be planted with trees as a shelterbelt. This policy has yet to be fully enforced (Mustafa, 2006) and adoption by farmers is proving to be slow (Myint, 2014). It is possible that the upfront costs that are associated with planting trees prohibit smallholders for taking up this practice, as argued later in this paper.

Sustainable land use practices and recovery of soil fertility are key to reversing the current land degradation trend in Sudan (Raddad and Luukkanen, 2007). This study proposes a sustainable land management (SLM) strategy using *A. senegal* agroforestry, where sorghum is intercropped between *A. senegal*, in parallel with the restoration and reforestation of degraded hilly areas that currently have no other uses. *A. senegal* is a wide spread, Sub-Saharan tree legume, reportedly important for the sustainability of open parkland, agroforestry, and alley cropping systems in Sub-Saharan Africa (Bationo, 2007).

To estimate the net benefits to society associated with this integrated SLM and reforestation scenario, six steps were undertaken:

- *First, establishment of the baseline scenario:* What will happen to the current land use configuration and the associated provision of ecosystem goods and services if land management practices are not changed?
- *Second, degraded landscapes and their land uses were identified:* This involved mapping the landscape characteristics and the suitable areas for restoration and SLM (see *Chapter 2* for maps and further information). For the purpose of this study, degraded landscapes were characterized by barren soil or agricultural land yielding very low returns to crop production.

[1] *A survey achieved in Sub-Saharan countries indicated that agricultural uses of land resulted in mean net nutrient removals from the soil of 22 kg of nitrogen/ha/yr (Crosson and Anderson, 1994).*

[2] *Collaborative reserve farmers work in formal partnership with the forestry adminstration.*

- *Third, designing a future land use scenario:* SLM and restoration interventions are defined and mapped out in a land use and land cover map (*Chapter 2: Future scenario*). Two restoration interventions were identified in Al-Gedaref to improve the ecological and economic productivity of degraded land, namely *A. senegal*-based agroforestry and reforestation through luban gum trees such as *Boswellia catering*, *Boswellia frererana*, and *Boswellia papyrifera*, hereinafter jointly referred to as *Boswellia* trees.

- *Fourth, changes in the flow of ecosystem goods and services that result from changing the baseline land use scenario to that which is stipulated in the future are modelled.*

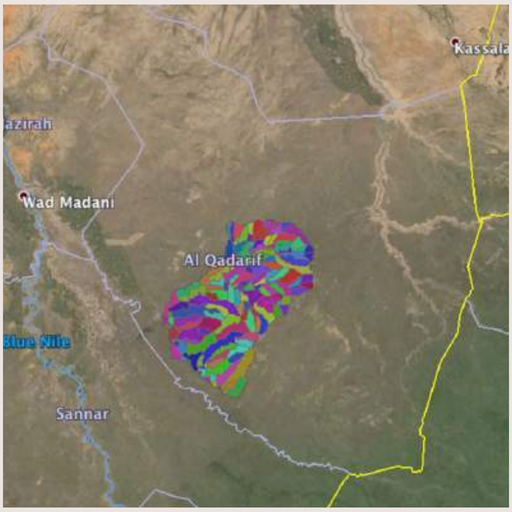
- *Fifth, valuation of changes in ecosystem goods and services resulting from the integrated restoration intervention are carried out* (*Chapter 3 to 9*).

- *And finally, sensitivity and uncertainty analyses were conducted* to observe how sensitive cost benefit analyses results are to changes in key variables such as prices and discount rates (*Chapter 10*).

FIGURE 1

Watershed where the valuation work took place within the state of Gedaref, Sudan

(from Myint, 2014)



02

The study area, valuation scenarios, and data

Study area

The study was undertaken in the southern-most watershed within the Al Gedaref State, including the villages of Hawata, Mafasa, and Sharman. The total area of the basin is 716 891 ha and lies between 12.6 to 14.4°N, and 33.6 to 36.4°E (*Figure 1)*. There are two main types of soil. Vertisols, the most predominant soil type (80 per cent of the total area), are heavy clay soils which form deep cracks from the surface downward when they dry out. They become very dry in the dry season and are sticky in the wet season due to a slow water penetration, and waterlogging may occur. Tillage is thus difficult, except for a short period between the dry and the wet season, which explains the mechanisation of this operation. Vertisols are further characterised by poor organic matter and nitrogen content (Ahmed and Sanders, 1998). The second type of soil is clay loam soil, which is less widespread (20 per cent of the total area) and essentially confined to the north-eastern part of the watershed.

The main cultivated crop is sorghum and to a much lesser extent, sesame. These rainfed crops are grown during the rainy season, which extends for about four months from June to September. The climate is semi-arid throughout the whole area with an average annual cumulative rainfall recorded during the period 1991-2010 of 557 mm.

Baseline land use scenario

In establishing the baseline scenario, it was assumed that the landscape will not change (see *Figure 2*) and that, given the lack of information and uncertainty and about the evolution of climate in the Sahel, the average annual weather pattern of the last 20 years is the best predictive value for the next 25 years. Hence, according to the present-day landscape configuration and assuming the average annual weather pattern of the last 20 years will be maintained for the 25 year time horizon, a biophysical analysis was used to estimate the yearly levels of soil erosion, soil moisture, carbon sequestration, groundwater infiltration, crop yields, fuelwood production, and Gum Arabic harvests.

While it is questionable to assume that the landscape and land uses will not change over 25 years, it would be daunting to hypothesize the potential evolution in the landscape and associated flow of ecosystems. Similarly, authors also did not attempt to predict how the climate patterns will evolve in this period and rather assumed that the weather pattern over the last 20 years is reproduced. While this may not be realistic in the face of a global warming, the assumption is not problematic for the sake of this study, since authors were focused on estimating the value of the difference in the flow of ecosystem services in the baseline

The typical soil – vertisol - found in eastern Sudan (left) and a barren hill (right)

versus future SLM land use scenario, both of which are subject to the same weather parameters in the analysis. Thus, relative as opposed to absolute values are of key relevance to the cost benefit analysis.

Degraded areas in the study area

The near-monocropping rainfed farming system practiced for decades in Gedaref has led to the destruction of the vegetation and the degradation of soil fertility. Aside from degraded agricultural soils, the landscape features many denuded hills with shallow soils and occasional trees, either communally or state owned - areas which could feasibly be integrated into a coherent restoration strategy. As argued in a growing body of literature, one evident solution to land degradation is to promote the planting, utilization, and regeneration of a native legume tree (Bationo, 2007; Harmand et al., 2012,). On the basis of this literature and fieldwork undertaken for this study, the following shows the design and justification for the land use restoration options that are subsequently valued.

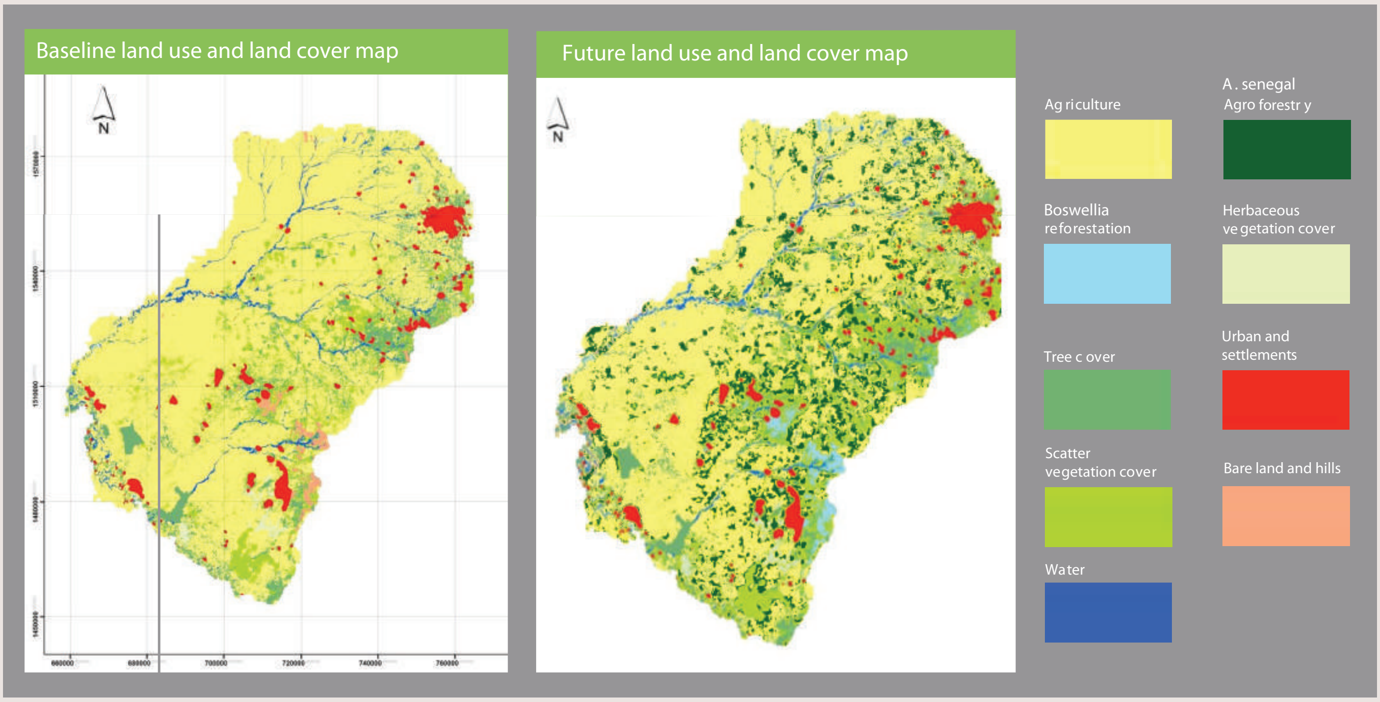
Future scenario: Designing the integrated restoration and sustainable land management intervention

The case for agroforestry

Agroforestry represents an approach to integrated land use involving the deliberate mixture or retention of trees and other woody perennials in crop or animal production fields. Following Nair et al., (1984), the benefits associated with woody perennials, including leguminous ones, can be distinguished as productive and protective. The **productive role** includes production of food, firewood, fodder, timber, and diverse Non Timber Forest Products (NTFPs). The **protective role** of woody perennials in agroforestry systems stem from their soil improving and conserving functions. These functions include fixation of atmospheric nitrogen, addition of organic matter through litter-fall and dead/decaying roots, modification of soil porosity and infiltration rates leading to reduced erosion potential of soil, and sun-shade, which helps keep moisture in the soil and eventually available for intercropping (Nair, 1984). Agroforestry also provides other indirect

FIGURE 2

Present and future integrated SLM and forest restoration land use scenarios in a watershed in Gedaref State, eastern Sudan



ecosystem services, including enhanced carbon sequestration rates and maintenance of the hydrological cycle. In terms of advising on suitable tree species to include in such an agroforestry system, fieldwork and interviews with the Sudanese Forest National Commission, suggested that *A. senegal* could be an interesting species to integrate within a crop production system. *A. senegal* is a leguminous tree species found naturally in the Sahelian-Sudanian zone. Its gum is internationally traded, of high quality, and tapped outside the sorghum harvesting season. Gum arabic can be tapped when a tree is between 5 and 20 years of age. Before the advent of large-scale mechanized farming *A. senegal* was traditionally integrated into the system of shifting cultivation called the bush-fallow cycle of gum cultivation (Olsson and Ardö, 2002). The tree was used for gum production for 15 to 20 years, interspersed with a short period of cultivation (4 to 6 years). Such a system is not currently widely practiced, as farmers are cash constrained and grow crops for subsistence. The integration of *A. senegal* trees with staple crops may help to diversify income sources, while also responding to food needs and improving soil fertility.

Productive functions of *A. senegal* include:

- **High quality gum arabic**, known locally as hashab gum. It is used in confectionary, beverages, pharmaceutical, artistic materials, photography, printing, and pesticides. Sudan is the world's largest gum arabic producer (Feteha, 2014);

- **Fuelwood from older trees** that no longer produce significant or good quality gum, and;

- **Fodder** for cattle, sheep, goats, & camels.

Protective and indirect functions of *A. senegal* include:

- **Soil erosion/runoff reduction**: the deep taproot and extensive lateral root system of the tree (Barbier, 1991) makes it effective in reducing runoff, increasing water infiltration, and trapping and stabilizing sediments. The problems of downward sedimentation and siltation in water reservoirs are thereby mitigated;

- **Carbon sequestration:** it can contribute to limit the emission of carbon dioxide(CO_2) though the storage of above and below-ground carbon within the woody biomass;

- **Nitrogen fixation:** the tree fixes atmospheric N_2, thus contributing to increasing crop yields and playing an important role in restoring soil fertility (Ong et al., 1996);

- **Soil moisture:** the microclimate created by trees can positively affect soil water content and improve plant growth, and;

- **Wind breaks**: reducing the risk and impact of wind erosion.

Agroforestry is thought to have a great adoptive potential amongst small-scale subsistence farmers in drylands, as it requires few capital inputs and low maintenance (Raddad, 2006). This was confirmed from focus groups with farmers and experts in the study area. Glover (2005) also provides evidence suggesting there is a willingness of local people in Gedaref to integrate trees in their farming systems as they may also provide fuelwood, timber, and other NTFPs. From a representative sample of household farmers and collaborative reserve farmers, Glover and Elsiddig (2012) found that 91 per cent of respondents considered integrated forest and cultivation (with or without grazing) as their preferred future land use system, as opposed to only cultivation.

The case for reforesting barren hills with *Boswellia* tree species

During the field work for this study, another land use restoration option was identified - reforestation of barren hills with Luban gum trees such as the *Boswellia* trees (known locally as tartar trees). Regarding who should have rights to or may have an interest in restoration efforts in communal areas, Carter (1996) and Current and Scherr (1995) argue that an effective forestry extension service may encourage farmers to plant trees on common land. This can especially be promoted amongst farmers with small landholdings, as they rarely integrate trees on their land.

During the field visit, *B. papyrifera* was identified by a farmer group and biophysical expert as effective for restoration due to their drought

TABLE 1

Land use and land cover changes under the baseline and SLM scenarios

	Baseline (ha)	Future (ha)
Agricultural land	527 413	417 133
A. senegal trees at 6 x 6 m spacing on agricultural land	0	110 023[5]
Reforestation on bare mountains/hillsides using *Boswellia* trees	0	12 984
Sum total size of watershed	716 891	716 891

tolerance and high value gum production potential. Additionally, the improvement or establishment of protective forests on ridge tops, hillsides, and near water bodies may help trap sediments, ultimately allowing for the creation a buffer zone of natural forest. This analysis does not value *Boswellia* trees for their productive uses, since it is unclear who would benefit from these goods, or how the rights of access to these communally owned bare hills should be distributed. Instead, the trees are valued for their contribution to soil stabilisation, carbon sequestration, and ground water infiltration, acknowledging that this will provides conservative values.

Defining the integrated sustainable land use and forest restoration intervention

The case for integrating *A. senegal* with staple crops in agricultural production systems is supported by the FNC, who advocates for an agroforestry[3] system based on a spatial mixture of *A. senegal* established at 6 X 6 meter spacing with sorghum between the rows of the trees. The 6 x 6 m spacing of trees is promoted by the FNC to ensure that machinery can pass unhindered between the trees. This corresponds to about 278 trees/ha[4]. On the basis of meetings with farmer groups, in the future integrated SLM and restoration scenario it was stipulated that the *Boswellia* trees be planted on the currently bare mountains which are either communally or state owned.

The total area suitable for agroforestry and increasing woody biomass cover on bare hills was calculated on the basis of the rainfall gradient. *A. senegal* is widely distributed and shows a remarkable adaptability to both drought and frost. It grows in areas with an annual rainfall of 200 - 800 mm (NAS, 1983). The State Ministry of Agriculture in Gedaref State requires 10 per cent of total farm area to be planted with trees (Mustafa, 2006), whereas experts from FNC call for a more serious uptake of agroforestry to combat the land degradation trends and depletion of groundwater. This study valued benefits derived from an increase in the total Acacia tree cover to 20 per cent on agricultural land (see *Figure 2* and *Table 1*). For the sake of simplicity, the future integrated forest restoration and sustainable land management scenario as simple the 'SLM scenario' in the remaining sections.

Methodology

To estimate the potential societal net benefits from the proposed SLM scenario, a household survey was implemented and complemented with detailed land use and land cover classification. The household survey was implemented in April 2014 to collect data related to socio-demographics characteristics of the households, their use of the environmental resources, crop production, agricultural practices, livestock, prices of the inputs and products and finally to get a deeper understanding of the households' livelihoods. 100 households in the village of Um Sagata were interviewed. The Sudaneese Forest National Comission advised the authors of this report to do field work in this village as there have been farmers manifesting interest in agroforestry practices within the village.

Details on the socio-economic household survey

The inhabitants of the refugee village in Gedaref where the interview was conducted were a mixture of internally displaced peoples from Darfur and neighbouring state Kassala, while the other inhabitants are refugees from Eritria who have inhabited the area for over forty years. The

[3] *The FNC often refer to this system as Tanguya. However, as there are diverging opinions as to what constitutes a Tanguya system, this report refers to agroforestry, as a more generic term.*

[4] *The FNC expects to develop this technique. The choice of 6 X 6 m spacing has been made from the advice of the FNC experts and also from literature (Mohamed, 2005; Radaad and Luukkanen, 2007).*

[5] *Represents land not cultivated due to planting of trees in fields, as discussed in the section on the study area.*

household survey showed the average age of household heads in the area was 49. There is on average 8.5 people per household, of which 3.6 work on-farm. Only 35 per cent of the 100 farmers interviewed were literate and the other 70 per cent (majority) had not studied beyond primary school. The average farm size is 11 ha, of which 92 per cent is dedicated to agriculture (sorghum, sesame, etc.), 5 per cent is under fallow, and 3 per cent is for other uses (pasture, forest, etc.). No land was found to be dedicated to agroforestry. The land around the village, including the farm land is state owned and leased out to the farmers. In the mid-1970s, when land resources were still abundant, the state allocated, through a long term lease, 4.2 hectares of land to each family, whether local or refugee (Bascom, 1998). Among the cultivated agricultural land, 63 per cent is dedicated to sorghum, 21 per cent to sesame, and 16 per cent to millet. The main livestock owned is sheep, goats, and cows (approximately eight per household). Farmers are allowed to grow crops on the leased land and entitled to sell their produce for commercial purposes; however, any trees that are planted would belong to FNC. Other data from the household survey used to inform this study is reported in *Appendices A* and *B*. These relate to price information, farm characteristics, and perceived constraints to the uptake of agroforestry.

A focus group organized with villagers in Um Sagata, to better understand their livelihoods (left), and a face-to-face interview with a villager in the school of the village (right)

Biophysical analysis

The land use and land cover classification exercise was implemented in May 2014 and involved the collection of relevant biophysical data and detailed ground-truthing of a land use cover map of the watershed, which was established on the basis of satellite imagery (Myint, 2014)[6].

This fieldwork established the basis for the modelling of biophysical production functions using AquaCrop, an integrated soil and water balance model, and a Soil and Water Assessment Tool (ArcSWAT) with a GIS plugin. ArcSWAT is a watershed scale model developed to predict impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions over long periods of time. These biophysical models depend on physical characteristics of the landscape, including soil type, precipitation, slope, and land cover, to name a few. The data inputs used are outlined in *Table A.C1* in *Appendix C*. Output from SWAT outputs on water infiltration and sediment stabilisation was used as a direct input into the economic valuations. However, to estimate the impact of additional soil moisture on agricultural yields, SWAT outputs were used as an input to AquaCrop. AquaCrop is an FAO crop-model that simulates yield response to water of different herbaceous crops. It is designed to balance simplicity, accuracy, and robustness, and is particularly suited to address conditions where water is a key limiting factor in crop production (FAO, 2014) (further details about the model is provided in the previous section on the study area).

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[6] *Accessible at: http://cmsdata.iucn.org/downloads/final_report_eld_18july__2_.pdf*

TABLE 2

Ecosystem goods and services valued and the valuation approaches used

Ecosystem good or service	Primary data source generator	Secondary data source generator	Biophysical impact	Valuation approach
Nitrogen fixation	Values on nitrogen fixation from the literature	→ AquaCrop	→ Impact on crop yields	Productivity change approach and market prices
Soil moisture	ArcSWAT	→ AquaCrop		Avoided fertilizer replacement cost
Sediment stabilisation	ArcSWAT modelling	→ Nitrogen and phosphorus Soil characteristics from literature	→ Impact on nitrogen and phosphorus	Market prices approach
Gum Arabic production	Literature on Gum Arabic production in Gedaref		→ Quantity of Gum produced	Market prices approach
Firewood production	Fuelwood production of **A. senegal** from expert interviews		→ Quantity of Firewood produced	Market prices approach
Ground water infiltration	Biomass estimates from expert interviews and link to carbon sequestration following IPCC Tier 1 guidelines	ArcSWAT modelling	→ Impact on water infiltration to the shallow groundwater aquifer	Market prices approach
Carbon sequestration	Biomass estimates from expert interviews and link to carbon sequestration following IPCC Tier 1 guidelines	Social cost of carbon estimates from the literature	→ Impact on CO^2 sequestered	Avoided damage cost using the social cost of carbon

Economic valuation methods used as part of this study

As highlighted in *Table 2*, three different valuation methods were used to value the benefits associated with future land use scenario. These are the: productivity change approach, market prices approach, and replacement and avoided damage cost approach. While all valuation methods have strengths and limitations, these were considered to be the ones able to optimally cater to the type of valuation question and data authors were able to collect within the time-frame of this study.

The productivity change method is used to estimate the economic value of ecosystem services that contribute to the production of commercially marketed goods. It is applied in cases where the products or services of an ecosystem are used, along with other inputs, to produce a marketed good, e.g., soil moisture which affects the productivity of sorghum crops. The economic benefit of improved soil moisture can be measured through increased revenues from greater agricultural productivity. Additional revenues are estimated as the difference in crop yields with and without erosion, multiplied by the unit price of the crop, less the costs of production (Barbier, 1995).

The market price method estimates economic values for ecosystem products or services that are bought and sold in commercial markets. It was used in this study to estimate the financial values of changes in fuelwood and gum arabic supply, because these products can be commercially collected or extracted as a result of the proposed restoration interventions. The economic benefit of greater availability of these products is thus simply the product of the quantity generated times the price at which the products may sell, less the costs associated with the productions. There are some limitations associated with this approach, notably as the true economic value of goods or services may not be fully reflected in market transactions due to market imperfections and/or policy failures.

Moreover, there may be significant seasonal or inter-year variations. To account for this uncertainty, authors used a repeated random sampling technique of price variables known as Monte Carlo simulations. This technique also allows confidence intervals to be constructed around the estimated NPV of restoration (Naidoo and Ricketts, 2006). The market price method cannot be used to measure the value of larger-scale changes that may affect overall supply of the good and alter prevailing prices, however, changes within a single watershed in Gedaref are assumed to be unlikely to affect the global supply of gum arabic. Moreover, the additional fuelwood deriving from *A. senegal* agroforestry is marginal, compared to overall demand within the region.

The avoided damage and replacement cost methods estimate values of ecosystem services based on either the costs of avoiding damages due to lost services, or the cost of replacing ecosystem services. They assume that the costs of avoiding damages or replacing ecosystems or their services provide useful estimates of the value of these ecosystems or services. The methods do not provide strict measures of economic values, which are based on peoples' maximum willingness to pay for a product or service. Instead, it is based on the assumption that if people incur costs to avoid damages caused by lost ecosystem services, or to replace the services of ecosystems, then those services must be worth at least what people paid to replace them. Thus, they are most appropriately applied where replacement expenditures have actually been, or will actually be made. Since it is unlikely that farmers in Gedaref will be able to afford using fertilizers to offset losses in soil erosion in the near future, only the value of enhanced soil moisture and nitrogen fixation was included in calculating the overall gains to the farmer of adopting agroforestry. On the other hand, the replacement cost was used to value the groundwater recharge function. As villagers incur regular expenditures associated with water purchase, when natural water holes run dry, this valuation approach is appropriate in estimating avoided expenditures associated with a higher shallow-groundwater table. For more information about the use of the replacement cost methods as applied to soil erosion, the reader is referred to Barbier (1995).

The following sections value the different ecosystem goods and services derived from integrated sustainable land use and forest restoration scenario, as opposed to a continuation of the baseline land scenario. In particular, the benefit of enhanced nitrogen fixation and soil moisture are valued, through their contribution to enhanced agricultural yields. Benefits associated with soil stabilisation, carbon sequestration, fuelwood, and gum arabic production are also valued through estimation. Finally, the costs of implementing and managing the integrated sustainable land use and forest restoration are considered.

Results

To measure whether investing into the integrated restoration and sustainable land use intervention is socially desirable relative to doing nothing (baseline scenario), this study proceed as follows.

Firstly, discounted values of benefits under the baseline scenario are subtracted from those earned in the future SLM scenario for each ecosystem good or service, S *(Equation 1)*. The individual benefit streams are summed over a 25 year time horizon to obtain the aggregate present value (PV) of benefits. A discount rate of 5 per cent is used for the sake of illustration throughout the paper. *Chapter 9* presents the results for three different discount rates.

$$PV_{BENEFIT\ OF\ SLM} = \sum_{t=0,s}^{24} \frac{BENEFIT_{s,SLM} - BENEFIT_{s,BASELINE}}{(1+r)^t} \qquad \text{(Equation 1)}$$

Secondly, implementing and managing the SLM scenario is associated with costs over and above the baseline costs. Discounted costs under the baseline scenario are subtracted from those under the future SLM scenario to obtain the aggregate PV costs (see *Chapter 8*).

$$PV_{COST\ OF\ SLM} = \sum_{t=0,s}^{24} \frac{COSTS_{s,SLM} - COSTS_{s,BASELINE}}{(1+r)^t} \qquad \text{(Equation 2)}$$

Thus, to estimate the net benefit of the future SLM scenario, the total discounted costs are subtracted from total discounted benefits to yield a NPV of the intervention in terms of 2014 Sudanese pounds (the current unit is SDG). This is an absolute measurement of the projects net benefit.

$$NPV_{BENEFIT\ OF\ SLM} = PV_{BENEFIT\ OF\ SLM} - PV_{COST\ OF\ SLM} \qquad \text{(Equation 3)}$$

The majority of the PV calculations used for this report are found in the appendices.

03

The value of nitrogen fixation, soil moisture, and avoided sedimentation resulting from agroforestry

As previously mentioned, one potential solution to land degradation is to promote the planting and regeneration of native legume trees as part of an agroforestry system (Harmand et al., 2012). Starting from the hypothesis that large-scale adoption of *A. senegal* agroforestry systems can have important consequences on land productivity, the following seeks to separately estimate the benefits of avoided erosion as well as enhanced nitrogen fixation and soil moisture levels. Unfortunately, there is not one integrated biophysical valuation approach that permits simultaneous valuation of these three services in terms of their contribution to agricultural productivity. Instead, a number of methods are combined, as briefly explained in the following, and further elaborated in the next three chapters.

- To assess the impact that *A. senegal* agroforestry may have on soil moisture levels a SWAT model was developed (see Myint, 2014). The model outputs are used to parameterize an integrated crop-water balance model to estimate the impact of soil moisture on sorghum productivity. Enhanced crop productivity is valued using market prices.

- To estimate the benefits of enhanced nitrogen fertilization, authors used agronomic experimental studies evaluating the impact of *A. senegal* agroforestry on the level of nitrogen fixed in the soil. They then used the value within the integrated crop-water balance model to estimate the impact of the enhanced nitrogen fixation. The change in the sorghum productivity was subsequently valued using market prices.

- To estimate the benefits of reduced soil erosion, SWAT was used to establish how *A. senegal* agroforestry will impact soil erosion levels relative to the baseline scenario. The benefits of reduced sedimentation are subsequently valued by estimating how much it would cost to replace the soil nutrients by an equivalent amount of artificially applied nitrogen and phosphorous.

Evolution of grain and crop residue yields due to soil moisture and nitrogen enhancement

To establish how land productivity will evolve over a 25 year time horizon under the SLM scenario, the AquaCrop model was used. Within the model, crop growth/production are driven by the amount of water consumed. The conceptual model at the core of the AquaCrop growth engine is shown in *Appendix C*. Similar to other crop-growth models, AquaCrop includes sub-model components (compartments) which depend on the following data:

- **Climate**: rainfall, temperature, evapotranspiration, and CO_2 concentration;

- **Soil:** number of soil horizons, thickness,soil water content, total available water, saturated hydraulic conductivity, drainage characteristic, curve number, readily evaporable water;

- **Crop characteristics:** crop water productivity, maximum canopy cover, duration of flowering, maximum effective rooting depth, harvest index[7], and;

- **Crop management:** soil fertility stress factor (proxy for soil nitrogen content), soil surface covered through mulch, irrigation schedule, and presence of soil bunds.

Table A.C1 in *Appendix C* shows the data sources that were used for the AquaCrop model. The following shows the model results for vertisol and clay loamy soils. The model was not run for different crop management regimes, as the household survey revealed that the major agronomic practices were very homogenous amongst farmers in the study area. The soil fertility stress factor was calibrated, which is a proxy for the amount of nitrogen present in the

[7] *These are crop specific biophysical values. Aquacrop default values for sorghum were used, with the exception of the harvest index, which was derived from Cirard-Gret (2002) and set to 25 per cent.*

soil. Agricultural practices that use large amounts of inorganic fertilizers may lead to low soil fertility stress (since nitrogen will not be a limiting factor of the potential yield), while in practice, the absence of such external inputs may lead to a high soil fertility stress factor.

Simulated sorghum yields as a result of enhanced soil moisture and nitrogen fixation for the baseline scenario

The average simulated yields obtained under the baseline scenario on the basis of the last 20 years of weather data, is 782 kg/ha for vertisol, and 811 kg/ha for the clay loamy soil. At these yield levels, the value of the soil fertility stress factor obtained is at its highest at 77 per cent. The high level of soil fertility stress confirms that soils in eastern Sudan are degraded and that agricultural practices are very extensive. The simulated average yields are similar to estimates found in the literature. In eastern Sudan, Raddad and Luukkanen (2007) report an average yield of 1000 kg/ha, while Ahmed and Sanders (1998) and Mustafa (2006) found slightly lower yields. The baseline yield is 193 kg/ha, which is also higher than the average yield obtained in 2013 according to the farmers interviewed for the study (see *Appendix A*).

However, the farmers noted 2013 yields were less due to exceptionally low rainfall. The difference may also be explained by the fact that AquaCrop does not take into account the loss of yields occurring due to biotic factors such as pest infestation, disease, insects, or increased striga. Simulated yields must be seen as an approximation located in the upper range of the actual distribution of yields obtained by farmers. Nevertheless, for the economic valuation the study is interested in differences between the simulated yield obtained in the baseline and SLM scenario, in which case the accuracy of the absolute magnitudes are irrelevant.

Simulated sorghum yields as a result of enhanced soil moisture and nitrogen fixation, and trees, for the SLM scenario

To forecast the evolution of sorghum yields under the SLM scenario, AquaCrop was used to simulate the impact of agroforestry according to its impact on nitrogen in the soil and soil moisture. The main impacts of *A. senegal* on cereal yields are their ability to fix N_2 and retrieve it from below the rooting zone of crops (which contributes to an increased nitrogen stock in the soil) while reducing runoff and enhancing water infiltration thanks to a 'shadowing effect'. Raddad (2006) compared a site under pure sorghum cultivation to one where sorghum was intercropped with *A. senegal* at 5 x 5 m spacing in the Blue Nile region in Sudan. It was found that *A. senegal* agroforestry systems allows topsoil nitrogen to increase by up to 30 kg/ha. Ovalle et al., (1996), Ndoye et al., (1995), and Jewitt and Manton (1954, cited by Ardö and Olsson, 2003) also suggest that *A. senegal* is a good N_2 fixer and is relevant for restoring soil fertility in eastern Sudan.

To estimate how changes in soil nitrogen and soil moisture affect yield simulations in AquaCrop, the effect of *A. senegal* on nitrogen levels was isolated, by changing the value of the soil fertility stress factor relative to its baseline value of 77 per cent (obtained through the steps specified in the section on simulated sorghum yields for the baseline scenario. The soil fertility stress factor is used as a proxy for soil nitrogen content in AquaCrop. The appropriate change in soil stress factor was deduced by cross-verifying experimental results on yields from Raddad (2006). It was found that the soil fertility stress factor is likely to decrease by 5 percentage points (from 77 per cent in the baseline scenario to 72 per cent under the SLM) when *A. senegal* trees are between four and ten years old, to an additional decreased 5 percentage points (72 to 67 per cent) after the tenth year.

ArcSWAT was applied to the same area to estimate the impact of enhanced soil water content in the SLM scenario, (Myint, 2014). A biophysical study for Sudan (Myint, 2014) found that soil moisture increases by on average 1.53 mm/yr in the SLM scenario relative to the baseline. As it was not possible to directly incorporate soil moisture in the parameterization of the AquaCrop model, the increase in soil moisture was integrated as if the equivalent amount of water was being added through a drip irrigation scheme.

Despite the positive impacts of *A. senegal* on the nitrogen and soil moisture, trees do compete with sorghum for space, leaving less room to grow crops With a 6 x 6 m spacing of trees, the amount of land lost per hectare from the presence of trees is equivalent to 12.5 per cent of the land (e.g., 1 ha of pure cropping = 0.875 ha pure cropping under agroforestry).

As a result, the global relationship between the production of sorghum under a pure cropping system and under an agroforestry system can be defined as follows:

$$Q_{SLM} = A\{Q_{baseline}[1 + f(N,W)]\} \quad \text{(Equation 4)}$$

, where Q_{SLM} is the yield under the agroforestry system (SLM scenario), $Q_{baseline}$ is the yield under the pure cropping system (baseline), *A* is proportion of land dedicated to crops under agroforestry on one unit of land (A = 0.875), and *f(N,W)* is the effect of increased nitrogen *(N)* and soil moisture *(W)* as a result of *A. senegal* on crop yield (estimated through AquaCrop as explained above).

The resulting consequences on sorghum yields and crop residues as a result of enhanced soil moisture, nitrogen fixation, and a reduction in effective cropping area are shown in *Tables 3* and *4*.

Figure 3 shows the simulated yields under the baseline and SLM scenario for each type of soil. It was observed that during the first three years sorghum production may decline, but after that (when the effect of the trees on the nitrogen content in the topsoil appears), the production becomes higher than in the mono-cropping cultivation system.

These results suggest that the change in competition of space, soil fertility, and available water may lead to an increase in average yield of 15 percent for the vertisol soils and 8 per cent for clay loam soils after the fourth year, and then an increase of 28 per cent for vertisol soils and 24 per cent for clay loam soil (*Table 5*). These results are in accordance with those of Raddad and Luukkanen (2007) and confirm the quality of the derived values for the soil fertility stress coefficients. *Table 6* shows the results for the crop residue (straw); the percentage increase is lower than for grain.

Estimation of the price evolution of grain and crop residues of sorghum

As shown by recent events, cereal prices can greatly vary over a short period of time. This can be due to significant changes in the forecast supply of grain (because of climatic events), changes in demand and consumption habits, or restriction on exports or imports of major sellers/buyers. Therefore, authors attempted to predict the evolution of wholegrain sorghum prices over the 25 year time horizon on the basis of time-series observations of annual sorghum prices in Sudan from 1991 to 2011 (recorded by FAO STAT). An Auto-Regressive Moving-Average (ARMA) model was used, and regressions and parameter estimates are shown in *Appendix D*, *Equation A.D1* and *A.D2*. On this basis, observed and forecasted prices are shown in *Figure 4* [8].

TABLE 3

Average simulated sorghum yield (kg/ha) according to the fertility stress factor

Value of fertility stress factor	Vertisol	Clay loam soil
20% (1st year in the baseline scenario)	782 (15)[1]	811 (15.2)
25% (SLM scenario after the 4th year)	899 (18.4)	880 (17.7)
30% (SLM scenario after the 10th year)	1002 (23.2)	1008 (24.3)

[1] Standard deviation in parenthesis

TABLE 4

Average simulated crop residue of the sorghum (kg/ha) according to the fertility stress factor

Value of fertility stress factor	Vertisol	Clay loam soil
20% (1st year in the baseline scenario)	2260 (40.2)[1]	2446 (27.7)
25% (SLM scenario after the 4th year)	2370 (47.7)	2470 (30.2)
30% (SLM scenario after the 10th year)	2801 (52.6)	3013 (37.3)

[1] Standard deviation in parenthesis

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[8] *The household survey undertaken in the area revealed the farm gate market price of sorghum to be 2.2 SDG/kg in 2014.*

FIGURE 3

Predicted evolution of the sorghum grain yields (kg/ha) under the baseline and SLM scenarios

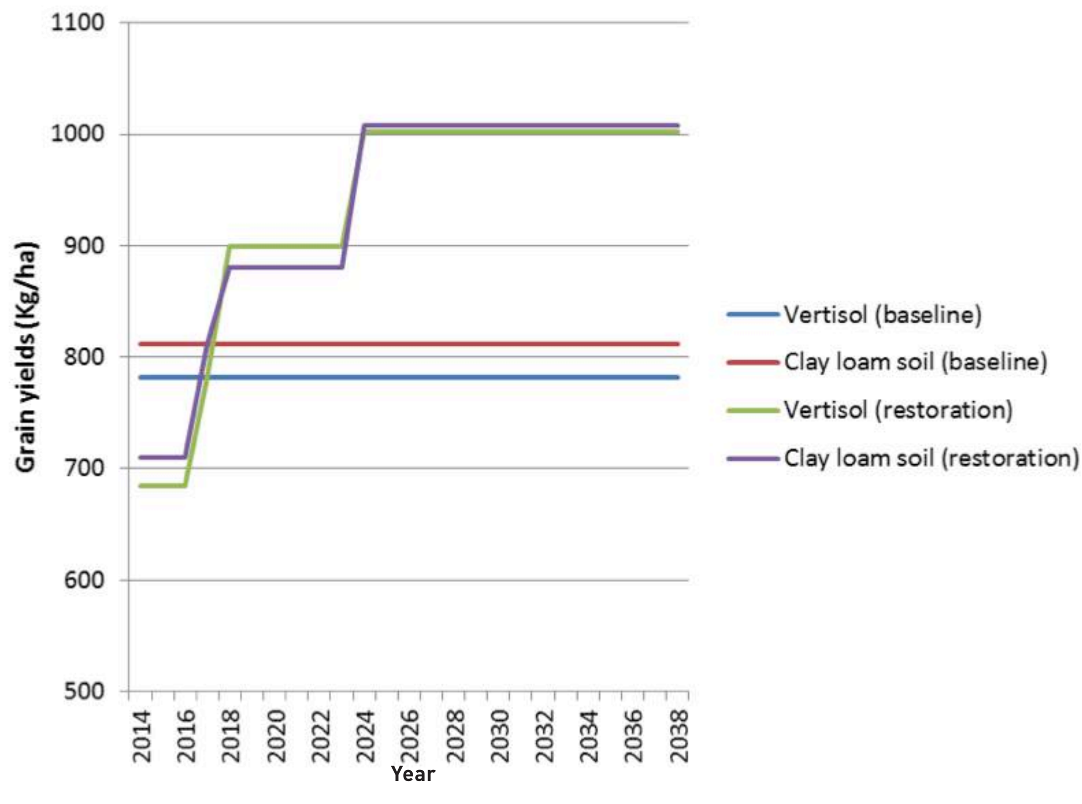
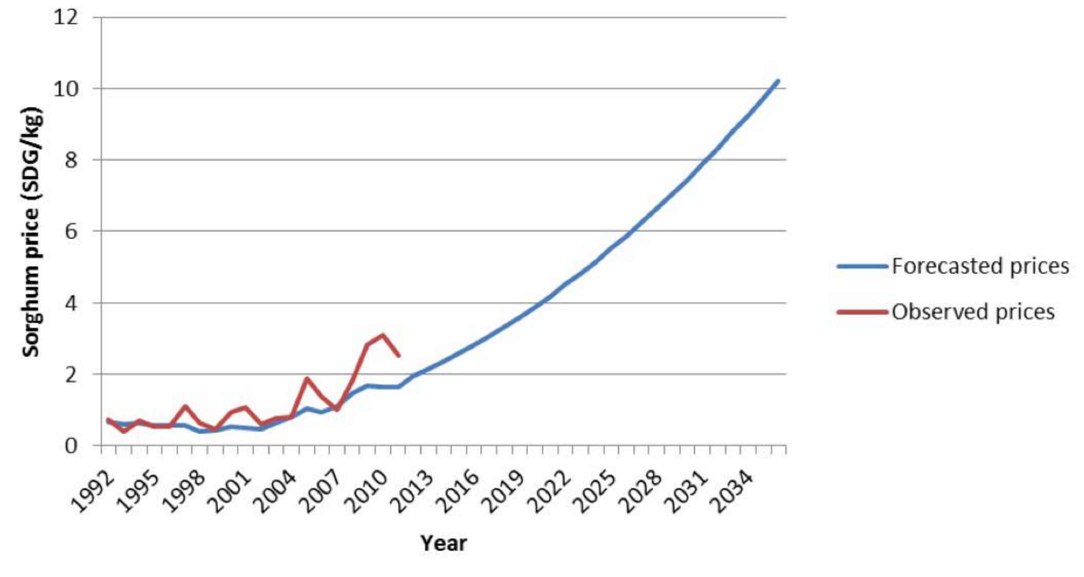


FIGURE 4

Observed and forecasted sorghum grain prices



Estimation of the present value of the impact of nitrogen fixation and soil moisture on yields

Having estimated the impact of agroforestry on yields as well as the predicted evolution of sorghum wholegrain and crop residue prices, authors could estimate the PV benefit of enhanced nitrogen fixation and soil moisture on yields ($PV_{sorghum\ yields}$) over the 25 year time horizon. PV is simply the predicted increase in yields, multiplied by the price and discounted to yield a PV estimate. The corresponding equation is shown in *Appendix E, Equation A.E1. Table 5* shows the PV estimates of sorghum yield per hectare over a 25 year time horizon for vertisol and clay loam soils. They indicate that 6 x 6 m *A. senegal* agroforestry can provide an impressive 20 per cent increase in the gross earnings associated with sorghum production. Prices are forecast to increase over the 25 year period, which suits the idea that pressure on land and natural resources will continue to increase in coming decades, and further contribute to increasing food prices. The household survey revealed that the price of the crop residues to be 0.18 Sudanese pounds (SDG)/kg in 2014[9].

The value of avoided soil nutrient loss

Estimation of annual nitrogen and phosphorus loss

The adoption of agroforestry can help decrease the rate at which soil is lost relative to the baseline scenario of pure sSorghum cropping. To tentatively value this ecosystem service the replacement cost method was used, which infers the value of what the farmer would pay to replace the nitrogen nutrients lost if he continued pure sorghum cropping instead of adopting agroforestry. To estimate the quantities of nitrogen carried off by soil erosion (Q_n,) an ArcSWAT model was developed to estimate the annual loss in sediments (S) (see Myint (2014) for details). As shown in *Table 6*, the model outputs demonstrate that annual soil erosion rates may be halved as a result of implementing the integrated SLM and restoration scenario. *Appendix D* shows how the equivalent loss in nitrogen and phosphorus is calculated. On this basis, the corresponding quantity of nitrogen and phosphorous lost is shown in *Table 7.*

TABLE 5

PV under the baseline and SLM scenarios of agricultural productivity induced by soil moisture and nitrogen fixation over 25 years (SDG/ha) discounted at 5 per cent

Type of soil	PVsorghum yield in baseline scenario	PVsorghum yield in future SLM scenario	PV of the additional sorghum yields under SLM scenario
vertisol	57 299 SDG	68 953 SDG	11 650 SDG
clay loam soil	59 805 SDG	69 607 SDG	9 800 SDG

TABLE 6

Rates of soil erosion under the baseline and SLM scenarios
(Myint, 2014)

	Baseline	SLM
Annual sedimentation loss	937 kg/ha	464 kg/ha

TABLE 7

Reduction in nutrient loss under the SLM scenario
(Myint, 2014)

$Q_{Nitrogen}$	0.15 kg/ha/yr
$Q_{Phosporus}$	0.19 kg/ha/yr

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[9] *SDG is the unit of the Sudanese currency (1 SDG = 0.175 US dollar in October 2014)*

Discounted average annual avoided cost of soil erosion over the 25 year time horizon

Two types of fertilizer can be found in Sudan, either urea (46 per cent of N) or NPK (14-18-18). On the basis of *Table 7*, if the nutrients lost in the baseline scenario (relative to the SLM scenario) were to be replaced by an equivalent quantity of inorganic fertilizer (NPK), it would be necessary to purchase the quantities shown in *Table 8*.

Results indicate that failure to adopt the SLM= scenario would mean that an additional 1.09 kg of NPK/ha would be needed to replace the lost amount of nitrogen and phosphorus in the baseline scenario. Given that the fertilizer cost is 10 SDG/kg[10] (18 USD/kg), the avoided annual cost associated with replacing nutrients lost in the baseline scenario relative to the SLM scenario is 11.4 SDG/ ha/ yr. Using *Equation A.F5* in *Appendix F*, the PV benefit associated with avoided nutrient loss over the 25 year time horizon using a 5 percent discount rate and assuming a fixed cost of fertilizer of 10 SDG/kg (prevailing market price in Sudan during the survey) amounts to 161.3 SDG/ha.

TABLE 8

Amount of nitrogen and phosphorus fertilizer (kg) needed to replace the soil stabilization gains achieved through the uptake of the SLM scenario

	Avoided nutrient loss
Nitrogen (N)	1.09 kg/ha/yr
Phosphorus (P)	1.04 kg/ ha/yr

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[10] *Price in 2014. A fixed price is used for the analysis.*

The value of gum arabic production

The production of gum arabic with *A. senegal* over the 25 year-period

To estimate the increase in production of gum arabic that may result as a consequence of the adoption of *A. senegal* agroforestry in Gedaref, authors used the results reported in Rahim et al., (2007), which were backed up by findings in Mohamed (2005) and Mustafa (2006) and shown in *Table 9*. The collection of gum starts in the 5th year after planting and continues until the 25th year. Peak production is reached between the 10th and the 20th year. The tapping and gum collection season runs from October until February. The first collection starts 40 days after tapping, then continues every 15 days after the previous collection. In a collection season, between three and six collections can be carried out. When the trees are 25 years old, they are cut and used for firewood. *Table 9* gives the level of production assumed.

TABLE 9

Production of gum arabic according to age of the tree

Based on Rahim et al. ,2007

Gum arabic production	kg/tree	Production/ha (278 trees/ha)
5th to 9th year	0.12	31.97
10th to 20th year	0.40	111.89
21st to 25th year	0.23	63.94

Estimation of the evolution of gum arabic prices

Gum arabic has few local uses, but is demanded on the international market, mainly by the pharmaceutical and food industries. Sudan is historically known to be a major exporter, but during the past 30 years, production in Sudan shows alarming signs of overall decrease and substantial annual variation. From the 1960s to the 1990s, average production declined from 46,000 to 28,000 metric tons. This led many importers to seek alternative sources of supply and to turn to manufactured substitutes. During the 1990s world exports started to pick momentum again, however exports from Sudan almost remained the same, due to stagnating production as well as the growing competition of other exporters (Rahim et al, 2007). Sudan has thus gone from being a monopoly price setter to a price taker. For the purpose of valuing the benefits of enhanced *A. senegal* agroforestry, farmgate prices for gum arabic were elicited in the responses to the household survey (*Appendix A*). Over the past five years (2009 - 2014), prices for gum arabic have varied from 3 to 13 SDG/kg. For the 25 year analysis, an average price of 7 SDG/kg was used as a reference point, accounting for possible inter-year price variations, for which a sensitivity analysis is conducted in *Chapter 10*.

It should be recalled that market prices are affected by various tariffs, subsidies, or taxes. Financial/market prices are therefore not a sufficient indication of societal benefits, in case of government interference. To calculate the extent to which *A. senegal* agroforestry within Gedaref may increase the net-wealth of Sudan's society, authors also valued the production of gum at international parity prices, using the Nominal Protection Coefficient (NPC) for production in Sudan reported in Ghada et al. (2014). The NPC is an indicator of the nominal rate of protection for producers measuring the ratio between the average price received by producers at farm gate, including payments or taxes per tonne of current output, and the border-equivalent price (global prices adjusted for costs of transport, marketing and processing) measured at farm gate level (OECD, 2000).

Ghada et al., (2014) estimated the NPC for gum arabic to be 0.92 for 2011 - 2012, meaning that the Sudanese value chain gives rise to lower income than would be the case in an economy which applies international parity prices. This result indicates that gum arabic production is taxed in Sudan, which undermines farmer profits and hence farmer incentives for taking up gum production. Authors furthermore assume that demand for Sudanese gum is perfectly elastic on the world market and therefore that additional supplies of gum arabic will not affect world market prices, in line with claims that Sudan has become a price taker on the global market for gum (Rahim et al., 2007).

Estimation of the present value of gum arabic production

Within the watershed where the analysis was conducted, there is no known production of *A. senegal*. Hence, PV benefit is that which is earned over and above zero gum production in the baseline scenario, according to *Equation A.G1* in *Appendix G*. On this basis, the PV benefit of gum arabic production through implementation of the SLM scenario is 6,525 SDG/ha (1140 USD/ha), or 460 SDG/ha/yr (75 USD/ha/yr) based on the annuity value of the PV of future benefits for a discount rate of 5 per cent (*Table 14*), The production of gum arabic can help enhance smallholder livelihoods and reduce inter-year variability of their income, since gum arabic tapping takes place outside the grain harvesting season. Costs associated with planting and harvesting gum arabic is integrated in the aggregate cost analysis in *Chapter 9*.

05

The value of fuelwood production

According to local sources *A. senegal* in Gedaref can grow to a height of 6 meters, depending on the climatic zone. Dr. Isam from FNC (personal communication, 2014) argued that the amount of fuelwood produced through the pruning of trees is negligible. However, at the end of the tree's 25-year rotation when it no longer produces gum arabic, it may be cut down and sold as fuelwood. According to another forester at the FNC, the production of firewood from a 25 year old tree could be 0.07 m^3 of fuelwood (or 70 litres), equivalent to about 20 m^3/ha assuming that there are 278 trees/ha (6 x 6 m spacing) (Dr. Isam, personal communication, 2014[11]).

Furthermore, on the basis of the results provided in the household survey (*Table A.1.1*), fuelwood prices have been estimated to 35 SDG/m^3. To account for variations in fuelwood prices over a 25 year time horizon, a sensitivity analysis is conducted in *Chapter 10*. Using *Equation A.G2 (Appendix G)*, authors found that the PV benefit of enhanced fuelwood supply was equivalent to 212 SDG/ha (or 36/USD/ha) over the 25 year time horizon, using the discount rate of 5 per cent. The value of fuelwood production is thus relatively minor compared to the value of other ecosystem services (valued above) provided in the SLM scenario.

06

The value of enhanced land productivity

On the basis of above analysis, the overall change in the value of agricultural land may be estimated, as a result of a change in the agro-ecological conditions of soil and the new production of fuelwood and gum arabic. To do so equation *Equations A.E1, A.G1* and *AG.2,* were summed to obtain the PV benefit of enhanced land productivity according to *Table 10.*

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[11] This local testimony was used for estimates here, although the figures appear lower than other estimates in the literature. Authors believe the overall analysis is underestimated (see www.worldagroforestry.org/treedb/AFTPDFS/Acacia_senegal.pdf)

TABLE 10

Present value of overall enhanced land productivity over 25 years in SDG/ha

	Vertisol	Clay loam soil
$PV_{\text{additional nitrogen and soil moisture on sorghium yields}}$	11 654	9 802
$PV_{\text{gum arabic}}$	6 007	6 007
PV_{firewood}	212	212
$PV_{\text{enhanced land productivity}}$	17 873	16 021

07

The value of shallow aquifer recharge

Although local communities in Gedaref are accustomed to buying water, the community is negatively impacted in the dry season when water points tend to dry up. The SWAT analysis showed that adoption of *A. Senegal* agroforestry and reforestation efforts will help improve water infiltration *(Table 11)*. This will increase the availability of water at the water points (Myint ,2014), which translates into 'reduced' or 'avoided' costs associated with the purchase of water. Complementary to this biophysical assessment, the household survey from April 2014 showed that the avoided cost of purchasing water is 42 SDG/ m^3.

It should be noted that the contribution to plant yields from increased soil moisture as calculated in *Chapter 3* is different (though estimated jointly in SWAT) from the values obtained for ground water percolation that contribute to shallow aquifer recharge.

Table 11 shows the main outputs from the ArcSWAT analysis with respect to average yearly changes in aquifer recharge and surface runoff, been converted from millimetres into cubic meters, equivalent at the watershed level. The figures demonstrate the extent to which adding more trees can be beneficial to enhanced groundwater infiltration and sediment stabilisation and reduced runoff. Given that ground water recharge varies annually depending on rainfall, authors used average annual infiltration, sediment and run-off rates from climatic data observed for the area over the last 20 years (see Myint 2014 for further details).

The present value of enhanced shallow aquifer recharge over the 25 year time horizon is estimated according to *Equation AH.1* in *Appendix H*. On this basis, the value over the 25 year time horizon associated with enhanced aquifer recharge is in the order of 19,880/SDG/ha This should be seen as an absolute upper bound value, as explained in the discussion on the caveats of the study.

TABLE 11

Impact of shallow acquifer recharge under the SLM scenario using the ArcSWAT model
Source: ArcSWAT model (see Myint, 2014)

Shallow aquifer recharge in the baseline scenario	109.4 m^3/ha/yr *
Shallow aquifer recharge in the SLM scenario	146.3 m^3/ha/yr*
ΔChange in volume between baseline and SLM scenario	36.9 m^3/ha/yr
ΔChange in volume between baseline and SLM scenario for the watershed	4.5 million m^3/yr
PV per ha from the future SLM scenario over a 25 year time horizon (SDG/ha)	19,880 SDG/ha

08

The value associated with carbon sequestration

The additional carbon sequestered as a result of the implementation of the integrated sustainable land use and reforestation scenario is estimated using IPCC tier 1 methodology (IPCC, 2003). Following this methodology, we firstly calculated the total amount of above and below-ground living biomass associated with the SLM scenario. Carbon may also be stored in dead organic matter, but that is neglected here. On this basis, changes in carbon and carbon dioxide equivalent stocks were estimated as shown in *Appendix* I. As a result of the SLM intervention, an additional 2.4 to 3.3 tons of carbon are sequestered under *A. senegal* agroforestry scenario depending on the age of the trees relative to a pure sorghum production scenario. The planting of *Boswellia catering*, *Boswellia frererana*, and *Boswellia Papyrifera* trees on degraded lands, are projected to lead to an increase in soil carbon stocks of between 8.1 to 11.1 tonnes C per hectare over the 25 year time horizon.

Social cost of carbon (SCC) estimates are used to translate enhanced carbon storage into social benefits. SCC estimates the discounted value of the damage associated with climate change impacts that would be avoided by reducing carbon dioxide (CO_2) emissions by one metric ton in a given year (Anthoff et al., 2009). These damages include decreased agricultural productivity, damage from rising sea levels, and harm to human health related to climate change. SCC increases over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climatic change. This study used SCC estimates devised by an American interagency working group[12] (EPA, 2013).

The dollar equivalent of avoided damage is combined with above derived changes in total carbon dioxide equivalent stocks as a result of the SLM scenario, to estimate the PV of additionally sequestered carbon. The corresponding equation is shown in *Appendix J*. On this basis, authors found that the present value benefit of the additional carbon sequestered over 25 years is 28,000 SDG/ha (4,680 USD/ha), equivalent to 2,000 SDG/ha/year (330 USD/ha/year) in annuity value using a 5 per cent discount rate.

[12] *A newly released report by the US Enviromental Defense Fund argues that the EPA 2013 estimates are too low, and the SSC estimates do not include costs of other major climate impacts, such as increased respiratory illness from higher pollen or ozone, the spread of insect-borne diseases such as Lyme disease, or the toll that ocean acidification on fisheries. http://costofcarbon.org/files/Omitted_Damages_Whats_Missing_From_the_Social_Cost_of_Carbon.pdf*

Costs of the *A. senegal* agroforestry system and planting of Boswellia trees

The analyses presented have shown the significant private and societal benefits associated with agroforestry adoption. On the basis of the private benefits alone, one may question why the use of agroforestry is not more widespread within the study zone. As shown in *Chapter 3*, there are a number of factors deterring farmers from engaging in agroforestry, one of which is the absence of credit to finance the initial investments.

To properly account for implementation and management costs associated with the trees as well as the impact on production costs of the intercropped sorghum in the cost benefit analysis, data was derived from expert interviews to complement the household survey. In the first year, agroforestry implementation costs are associated with the purchase and planting of the *A. senegal* trees. The intercropping of sorghum with trees changes the production cost of sorghum per unit of land compared to a pure sorghum cropping system (the baseline scenario). Production costs refer to the sum of the costs of land preparation, hiring of a tractor and a disk, seed purchase cost and sowing, weeding, and harvesting. The overall cost of sorghum production is lower in the case of agroforestry, because less seeds need to be used and weeding time is shorter. No extra costs are associated with land preparation, since with 6 x 6 m tree spacing it is still possible to use a tractor for seeding. By the fifth year, when gum arabic may be collected, there are management costs are associated with gum harvest and pruning. Finally in the last year of the rotation, there is a cost associated with cutting trees for firewood. The costs associated with the planting of *Boswellia* trees are only incurred the first year since it is assumed that trees are planted by the state on the bare hills of the watershed and no further costs are incurred. Costs are shown in *Table 12*.

TABLE 12

Production costs (SDG/ha) associated with the two scenarios

	Pure sorghum cultivation (Baseline)	A. senegal agroforestry system			Planting of Boswellia trees
		Sorghum production costs*	Implementation and management costs+	Total costs	
1st year	1325	1214	242	1456	302
2nd to 4th year	1325	1214	90	1304	0
5th year to 24th year	1325	1294	450	1744	0
25th year	1325	1294	880	2174	0
Total discounted costs (r = 5%)	19 608			24 461	302

*Costs associated with sorhgum production
+ Costs associated with tree planting

10

Costs and benefits of integrated restoration and sustainable land intervention

In this section, the NPV of *A. senegal* agroforestry to the individual farmer and a sensitivity analysis to study the impact of price changes on this is first shown. Next, NPV to the whole society based on direct and indirect impacts of the ecosystem goods and services shown above is demonstrated.

Net present value of *A. senegal* agroforestry to the individual farmer

As shown in the previous section, there are costs associated with agroforestry adoption. However, there are also many benefits associated with better long term sorghum yields and gum arabic harvests that can be collected outside the sorghum harvesting season. These elements are brought together to estimate NPV to the individual farmer of adopting agroforestry over a 25 year time horizon, as shown in *Appendix K*. This accounts for the value of enhanced yields (from enhanced soil moisture and nitrogen fixation), gum arabic and fuelwood production, as well as implementation, management, and production costs to the farmer. The value of avoided soil erosion as calculated by what it would cost to replace lost nutrients is not accounted for.

Farmers do not currently use fertilizers and are unlikely to be able to bear the future cost of fertilizer purchase, meaning that including this would overestimate benefits at the farmer-level. Results show that the NPV is 12,649 SDG/ha over a 25 year time horizon. *Figure 5* shows the flow of costs and benefits to the individual farmer over the time horizon. As argued in Barbier (1995), agroforestry (like other SLM practices) involves upfront direct costs as well as possibly changes in cropping patterns and loss of productive area, PV net returns to the farming system with trees is initially lower than without trees (Barbier 1995). However, because acacia agroforestry helps fix nitrogen in the soil and improves future soil moisture, PV net returns of a farming system with acacia trees will eventually exceed the returns in those without acacia trees. For the land use system modelled here, benefits exceed costs three years after planting trees. It should be noted that the NPV refers to actual farm gate profit received by farmers, rather than border equivalent net returns. As gum arabic from Sudan is almost entirely exported, NPV to the Sudanese is shown in the aggregate result section using border-equivalent values that correct for government taxation.

Sensitivity and uncertainty analysis

Because the prices of gum arabic and firewood are very uncertain (an uncertainty over which values these parameters will take introduces risk into the analysis), authors perform a sensitivity and uncertainty analysis to account for this. A repeated random sampling technique known as Monte Carlo simulations was used to assess to which extent the results are sensitive to the values of these prices, and also to calculate confidence intervals around the estimated determinist NPVs. Other authors have used Monte Carlo simulations to account for risk in economic analyses of forestry related projects (e.g., van Kooten et al., 1992). On the basis of 5,000 runs of gum arabic and firewood prices, with the assumed parameter distributions shown in *Table A.L1* in *Appendix L*, 5,000 values of each parameter per year were generated. From the simulations, confidence intervals were constructed around the estimated per hectare NPV to the farmer of adopting agroforestry (using a discount rate of 5 per cent).

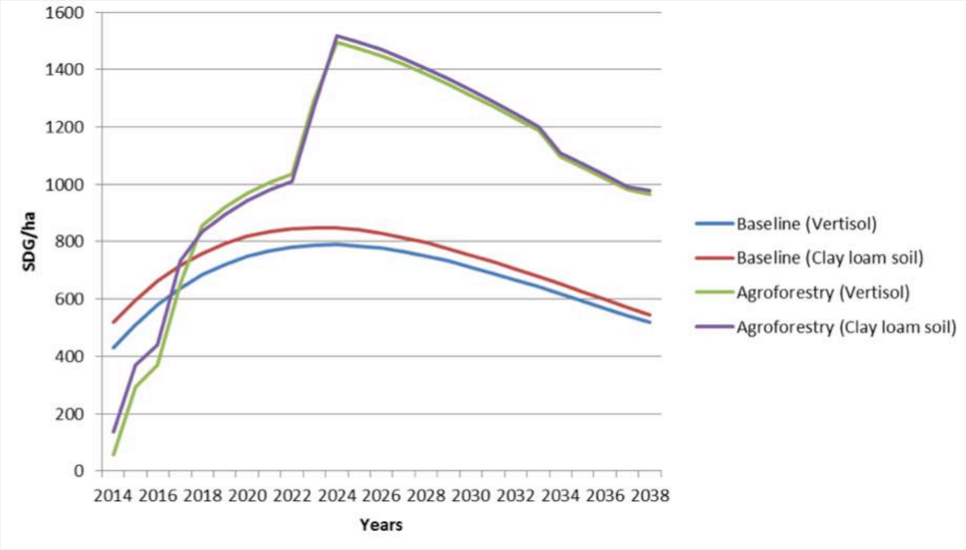
TABLE 13

Net Present Value (NPV) to the farmer at different discount rates (SDG/ha)

	r = 2.5%	r = 5%	r = 10%
Net Present Value to the individual farmer	19 119 SDG/ha	12 649 SDG/ha	5 750 SDG/ha

FIGURE 5

Comparison between the NPV of the baseline scenario and agroforestry when considering only the private (on-site) effects



Net present value to society and benefit-cost ratios

This section provides the private and societal net-benefits associated with *A. senegal* agroforestry and reforestation using Boswellia trees, using the methodology reported in *Chapter 2*.

Societal benefits include enhanced ground water infiltration and improved sorghum yields (due to improved soil moisture and nitrogen fixation), reduced soil erosion, gum arabic production, fuelwood, and enhanced carbon sequestration (the latter accruing to the whole world). Gum arabic production benefits are reported in financial and economic values.

Table 14 shows the NPV of implementing the SLM scenario to farmers, society and the planet. To estimate the sensitivity of the results to changing discount rates, the PV benefits and costs are calculated using 2.5, 5, and 10 per cent discount rates. In the following, authors report on some of the main results using a 5 per cent discount rate.

As shown in *Table 14*, farmers can benefit significantly from an uptake of A. senegal agroforestry. The benefit cost ratio suggests that farmer may enjoy a four dollar return on investment for every dollar invested in sustainable land management. This is equivalent to a present value net benefit of 12,650 SDG/ha (2,200 USD/ha) over 25 years, or an annuity value of 895 SDG/ha/yr (160 USD/ha/yr).

Additionally, if gum arabic prices remain as high as the two last years (2,800 to 3,200 USD/ton) then per hectare benefits to farmers could be 30–40 per cent greater, as shown in the sensitivity analysis in *Chapter 10*.

Comparing farmer level benefits to those enjoyed within the watershed as a whole, Sudanese society stands to enjoy even larger benefits associated with enhanced groundwater recharge and reduced soil erosion. Accounting for these benefits, the yearly discounted flow of benefits is in the order of 2,300 SDG (415 USD) for every sustainably managed hectare. If efforts were scaled up across the watershed as in

FIGURE 6

NPV to the individual farmer of enhanced land productivity (Monte Carlo sensitivity analysis)

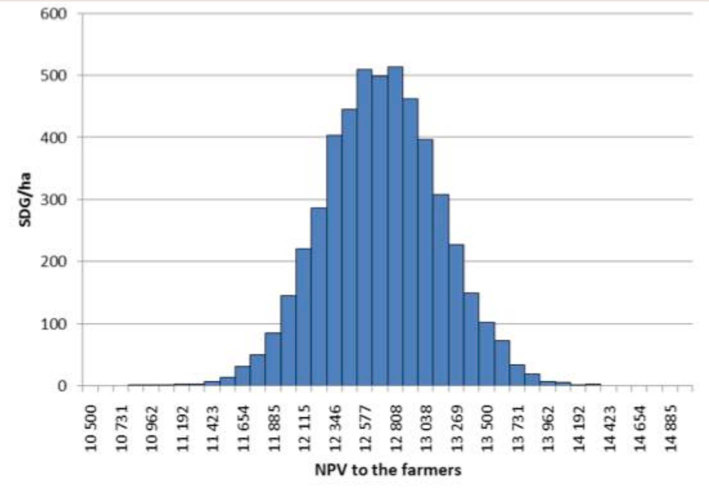


Figure 2, net benefits would amount to 3.9 billion SDG (700 million USD) over 25 years. This is an absolute upper bound estimate however, as societal value of groundwater is likely lower than its replacement cost, which has been used a proxy for societal value.

The global population will also benefit from increased storage of carbon in above and below ground biomass. With 120,000 hectares dedicated to A. senegal agroforestry and 10,000 ha to reforestation, the additional carbon stored provides benefits in terms in the order of about 28,200 SDG/ha (5,000 SDG/ha), or 2,000 SDG/ha/yr (350 USD/ha/yr) in annuity value. The aggregate value of all ecosystem services provided by SLM intervention amounts to 7.3 billion SDG (1.3 billion USD) for the whole watershed. Consulting the benefit cost ratio, this implies that for every Sudanese pound invested in sustainable land management another 12.8 SDGs of local, national, and global benefits are created.

Finally, it should be noted that per hectare values cannot be extrapolated in space, since ecosystem services are non-linear and place-dependent. Therefore, if the area subject to A. senegal agroforestry was to be doubled within the watershed, it is not for that reason that net benefit estimates will necessarily double. Nevertheless, the estimates shown here provide a good indication of potential farm level and societal benefits associated with the SLM scenario.

TABLE 14

Net present values associated with implementing the SLM scenario in Gerdaref in SDG (1 SDG = 0.175 USD)

		r = 2.5%			r = 5%			r = 10%		
	Benefits	**PV per ha**	**Annuity per ha**		**PV per ha**	**Annuity per ha**		**PV per ha**	**Annuity per ha**	
A	Nitrogen fixation and soil moisture [15] on yields	**16,976.4**	**921.4**		**11,286.4**	**800.8**		**5,243.6**	**491.2**	
B	Fuelwood	**376.4**	**20.4**		**220.4**	**15.0**		**69.1**	**6.5**	
C	Gum arabic (using financial prices)	**9,020.0**	**489.6**		**6,007.1**	**426.2**		**3,289.1**	**308.1**	
D	Gum arabic (using international parity prices)	**9,112,7**	**494.6**		**6,531.8**	**463.4**		**3,575.5**	**334.9**	
E	Avoided nutrient loss	**183.7**	**10.0**		**160.9**	**11.4**		**108.2**	**10.1**	
F	Enhanced shallow aquifer recharge	**27,017.3**	**1,466.4**		**19,880.1**	**1,410.5**		**13,920.0**	**1,304.0**	
G	Enhanced carbon sequestration	**136,956.9**	**7,433.5**		**28,222.0**	**2,002.4**		**0.0**	**0.0**	
	Costs									
H	Boswellia tree planting costs	**302.0**	**16.4**		**302.0**	**21.4**		**302.0**	**28.3**	
I	Agroforestry implementation and management costs	**31,678.2**	**1,719.4**		**24,502.7**	**1,738.5**		**16,118.2**	**1,509.9**	
J	Baseline sorghum cultivation management costs	**25,027.3**	**1,358.4**		**19,611.8**	**1,391.5**		**13,324.5**	**1,239.8**	
K	Additional management/implementation costs under sorghum agroforestry (I-J)	**6,650.9**	**361.0**		**4,890.9**	**347.0**		**2,883.6**	**270.7**	
	Net benefits	**PV per ha**	**Annuity per ha**	**PV whole water-shed**	**PV per ha**	**Annuity per ha**	**PV whole water-shed**	**PV per ha**	**Annuity per ha**	**PV whole water-shed**
	Farmers in the souther watershed in Gedaref									
A+B+C-K (A+B+C)/K	Net benefit Benefit-cost ratio	**19,722** **4.0**	**1,070.4**	**2.2 billion**	**12,649** **3.6**	**895.0**	**1.4 billion**	**5,718.2** **3.0**	**535.7**	**0.6 billion**
	For the Sudanese society (lower bound)									
A+B+D+E-H-J (A+B+D+E)/H+K	Net benefit Benefit-cost ratio	**19,696** **3.8**	**1,069.0**	**2.2 billion**	**13,299** **3.5**	**943.6**	**1.5 billion**	**6,112.7** **2.8**	**572.6**	**0.7 billion**
	For the Sudenese society (upper bound)									
A+B+D+E+F-H-J (A+B+D+E+F)/H+K	Net benefit Benefit-cost ratio	**46,714** **7.7**	**2,535.4**	**5.5 billion**	**32,877** **7.3**	**2,332.7**	**3.9 billion**	**19,307.7** **7.2**	**1,848.4**	**2.4 billion**
	Global society (upper bound)									
A+B+D+E+F+G-H-J (A+B+D+E+F+G/H+K	Net benefit Benefit-cost ratio	**183,671** **27.4**	**9,968.9**	**22.3 billion**	**61,099** **12.8**	**4,355.1**	**7.3 billion**	**19,307.7** **7.2**	**1848.4**	**2.3 billion**

11

Discussion

Pressure on landscapes to deliver extractive or consumptive uses as well as meet demands for energy, food, and water is forecast to increase[13]. Such predictions emphasize the need to restore the productive capacity of degraded and deforested lands (Lambin and Meyfroidt, 2011). Restoring degraded landscapes offers a potential solution to the problems created by unsustainable land uses practices, where topsoil degrades at a significantly higher rate than it regenerates. From an economic perspective, SLM simply implies saving soil for future use. Land degradation is an economic problem if farming households ignore future gains from production or income generation associated with having healthy soils available. Reasons for ignoring future gains may result from insecure tenure, lack of understanding of SLM benefits, weak access to credit, or high private discount rates. The adoption rate of SLM will similarly be sub-optimal if any off-site or external costs are ignored in the farmer's decision-making process, which is typically the case. Payments for ecosystem services or other schemes to help compensate farmers for their efforts to society may encourage farmers to adopt SLM practices.

As shown in this paper, external benefits of SLM that do not directly accrue to the farmer are significant. In particular, this study shows that within a single watershed in Gedaref, the present value of aquifer recharge and carbon sequestration amount to approximately 50,000 SDG per hectare of sustainably managed land, over 25 years using a discount rate of 5 per cent. When accounting for long-term benefits in terms of enhanced nitrogen fixation, soil moisture, avoided soil erosion, and fuelwood and gum arabic production, the NPV benefits are 22 billion SDG (corresponding to 3.9 billion USD using the commercial exchange rate of October 2014).

From a Sudanese perspective it is of strategic, environmental, and economic relevance to ensure that it is in the interest of the farming population to adopt SLM practices. The likelihood that any Sudanese farmer would wish to invest in SLM and more specifically *A. senegal* agroforestry depends on a number of factors, discussed below.

Prior to the 1970s, much of rural land (whether agricultural or forestland) was unregistered, but customs ensured that unregistered lands were under common property. Land allocation for agriculture, forests, and pasture was controlled by tribes and inter-tribal collaboration. In 1970 however, the Sudanese government issued the "Unregistered Land Act" that stated that all unregistered land is de jure government land. According to Shazali and Ahmed, (1999), this act caused an administration vacuum in which neither the state nor traditional customary authorities could exercise effective control over forest resources and their sustainable management. Unsecured or ambiguous land tenure thus resulted in confusion about land delineation and rights. Tenure insecurity still prevails today.

In the survey undertaken by Glover and Elsiddig (2012) in the Elrawashda area in Gedaref, they found that more than half of the farmers lacked land tenure security due to leasehold or informal tenure. Furthermore, on government leasehold, national laws do not support farmers in owning land or trees. Some residents therefore refrained from planting trees on their farms due to fears of government officials then expropriating 'their land' as forest reserve (Glover and Elsiddig 2012). In Um Sagata, tenure insecurity was not considered the principle obstacle, possibly due to the high proportion of landowners in the village (*Appendix B*). The main obstacle was thought to be lack of knowledge or understanding of benefits associated with agroforestry and access to credit.

Investments which take a long time to yield benefits are particularly risky when long-term rights are not guaranteed. Timber trees are only fully grown after 10 - 80 years. Fruit trees are usually not harvestable before the age of 4 or 5 years but may be productive for decades. *A. senegal* trees similarly do not start producing gum arabic until 5 years after they have been planted. Moreover, the actual pay-offs can be highly variable from one year to another. Profit expectations are therefore another important determinant of whether farmers may want to plant trees.

[13] *According to estimates from Mckinsey and Company, 175 – 220 million ha of additional cropland would be needed to meet the expected increase in food demand alone.*

Many authors argue that decades of distortionary economic policies in Sudan, such as an overvalued exchange rate, prohibitively high export taxes on gum arabic and monopolistic marketing practices by the government-owned Gum Arabic Company, have undermined the comparative returns to gum arabic to farmers (Barbier, 2000). Interestingly, even when gum arabic farm gate prices were rising in the 1980s, the immediate farmer response was not one of lessening resource degradation. Rather, there is evidence that higher prices led to the over-tapping of trees that were then killed in the process (UNSO, 1983). According to Larson and Bromley (1991), the desperate poverty of the farming population meant that the need to ensure the food security of the family overrode any future environmental costs associated with over-tapping[14]. A second reason why a higher gum price may have induced deforestation relates to the expectations of the farmers. After decades of low consumer prices, farmers most likely expected the price to be transitory rather than permanent. With a transitory price increase however, the value of standing trees does not fundamentally change, but the incentive is created to intensify extraction to earn higher short-term returns.

This may be changing now, as gum arabic prices have been soaring in recent years. Prices for top-quality gum arabic are currently between 2,800 and 3,200 USD/ton according to the state-run Gum Arabic Board (Feteha, 2014). Moreover, the Sudanese government undertook positive steps towards deregulation of the Gum Arabic Company concession rights in 2009 and established the Gum Arabic Council for Free Gum Arabic trade in domestic and export markets, to provide incentives for producers to take up gum arabic production (Ghada et al., 2014). Sudan is furthermore boosting loans to farmers and providing labourers with low-cost housing in a bid to double harvests[15].

Empirically speaking, access to credit, free seedlings, or other planting materials, has shown to be an important factor in facilitating uptake of the integration of acacia trees with crops in mechanised rainfed agricultural schemes (Fahmi et al., 2014) and with regards to SLM practices more generally (FAO, 2013; Bationo 2007; Gibreel 2013). On the other hand, lack of dissemination of ideas and information prevents the spread of agroforestry systems. Limited experience and low capacity among national extension services in both traditional and new agroforestry systems means that farmers are often reluctant to adopt these systems (FAO, 2013). Fieldwork undertaken as part of this study show the same results since the most important identified barriers agroforestry uptake are the lack of access to credit and the lack of knowledge about the benefits of agroforestry and 'how to do it' (*Appendix B*). This result matches study findings that in the first couple of years of the agroforestry system implementation, private returns are negative relative to continuing pure cropping.

Yet, Sudan has a target of annual shipments for exports of 300,000 tons by 2016, up from 63,000 tons in 2013. According to the Secretary General, Abdelmagid Abdelgadir, of the Sudanese Gum Arabic board it is an unrealistic target due to structural constraints such as labour shortages during the Gum Arabic harvesting season (Feteha, 2014). However, this study argues that if *A. senegal* is mainstreamed into crop farming systems as opposed to grown in plantations only, then most or all of the necessary labour supply may come from the farming family itself, since the gum harvest occurs during the dry season when work in the farm itself and off-farm work opportunities are few. It should also be mentioned that there is no incompatibility with continued mechanisation and the *A. senegal* agroforestry scenario envisaged here. The 6 x 6 m spacing of trees is promoted by the FNC to ensure that machinery can pass unhindered between the trees.

Through the cost benefit analysis presented in this paper we have shown that boosting *A. senegal* agroforestry, can help improve farmer livelihoods by providing much needed off-season income and more productive soils. Additionally, A. senegal-based agroforestry also provides other valuable ecosystem (such as water infiltration, carbon sequestration, and soil stabilisation) to a broader stakeholder group. As such, authors make a case here for ensuring that new policies and initiatives are steered towards providing sufficient extension services, clarifying land tenure ambiguities, solidifying rights to plant and harvest trees on both leased and private lands, and potentially revising the domestic gum arabic tax reform.

As highlighted in Barbier (2000), poor rural smallholders can collectively benefit from sensible economic policies that allow producers to sell at

[14] In economic terms, at low-income levels the marginal utility of income is large. In this case future environmental costs to the household are small and resources are used intensively or depleted in the short run.

[15] This is done in an attempt to trying to diversify its economy after losing control of about three-quarters of its oil output when South Sudan seceded in 2011.

prices that are closer to border-equivalent levels. From the farmers' perspective, maintaining the real producer price for gum arabic over the long term is crucial to ensuring that farmers have appropriate incentives to rehabilitate and cultivate gum trees as part of their cropping systems. Finally, there is also a case for reforesting degraded public lands, (e.g., the barren hills in Gedaref) and designing an effective benefit sharing schemes to ensure that communities have sufficient incentives to plant, nurture, and care for these areas.

Furthermore, other non-economic constraints to the adoption of this practice exist but have not been studied here. The recently published study of Fahmi et al., (2014) identifies the determinants of acacia tree integration with crops in mechanised rain-fed agricultural schemes forming agroforestry parklands. They found that constraints related to the prevalence of agroforestry practices included the absence of extension services and planting materials, unfavourable land and tree tenure, the destruction of trees/crops by animals, and the practice of renting land for monocrop cultivation. Thus, an increased adoption of sustainable agroforestry for more productive farming requires several actions at community and state levels.

Caveats

The economic valuation presented here attempted to comprehensively value the contribution of *A. senegal* agroforestry and the restoration of barren hills in the landscape. However, there are certain caveats that should be taken into account when considering the results:

- The fodder and browsing value of *A. senegal* to livestock is not included in the valuation study. This is not considered a major issue, because when *A. senegal* is subject to browsing pressure it does not produce much gum Arabic (Dr. Bashir A. El Tahir, personal communication 2014). Hence, when these trees are planted, farmers have to make a choice whether to use them for gum or fodder. Moreover, given that the current price of fodder in the area is very low (0.18 SDG/kg), farmers favour the production of gum over fodder. This certainly explains why fodder is not accounted for in other economic analyses of *A. senegal* production (e.g., Mustafa, 2006; Rahim et al., 2007);

- The seed production value of *A. senegal* was not factored into the analysis as the value of this service is considered to be minor for *A. senegal* relative to the value of high Gum Arabic produce and other ecosystem services;

- Providing accurate estimates of costs associated with implementing the SLM scenario presented here was a difficult task. Some major costs include the provision of extension services to farmers and transaction costs associated with establishing effective schemes to incentivize the planting, management, and benefit-sharing associated with trees on public lands (the barren hills in the landscape). These are types of cost factors that were not integrated in the analysis at present;

- In the future, authors would ideally also prefer to do a separate cost benefit analysis of the value of the contribution of agroforestry versus reforestation to reducing land degradation. Authors were not able to strictly separate the regulating ecosystem service benefits (soil stabilisation and water infiltration) from the interventions, but because of their respective magnitude, they believe that 80 to 90 per cent of monetary benefits estimated in this analysis can be attributed to *A. senegal* agroforestry;

- *A. seyal,* another nitrogen fixating tree species, yielding a lower grade gum but a more regular and stable supply of fuelwood than *A. senegal*. It could also have been valued as part of a potential future agroforestry scenario, but given the rising demands for high quality gum and the Sudanese government's interest, authors considered this a pertinent moment to focus on the potential contribution to *A. senegal* to farmers and broader society;

- In valuing the benefit of enhanced water supply, authors used the replacement cost method. This method is based on the assumption that spending that is avoided with the replenishment of the natural water-whole is worth at least what people paid to replace the water when it runs dry. This may be an exaggeration, since the increase in groundwater generation may lower overall demand for 'substitute water' purchase, and thus lower the price relative to the price used in this valuation study;

- This study did not attempt to measure benefits to biodiversity that could be provided through increased tree cover, and;

- None of the valuation methods used provides strict measures of economic values, which are based on people's maximum willingness to pay for a service. But stated preference valuation methods like this that are used for ex-ante valuation, are subject to other biases and uncertainties. Moreover, for the purpose of conveying messages to policy makers, it is more relevant to estimate the impact of land use changes on actual expenditures rather than the maximum that citizens are willing to pay for a service.

Conclusion

Land degradation and deforestation threaten Sudan's prospects for long-term food security, sustainable development, and peace. According to UNEP (2007), the rapid erosion of environmental services occurring in several key parts of the country are among the root causes of decades of social strife and conflict. Agriculture is the largest economic sector in Sudan, and is at the heart of some of the country's most serious environmental problems. In particular, disorganized and poorly managed mechanized rainfed agriculture, which covers an estimated area of 6.5 million hectares, has been exceptionally destructive -leading to large-scale forest clearance, loss of wildlife, and severe land degradation. It is therefore imperative that these current trends are reversed through appropriate land use management interventions.

The analysis presented here provides encouraging results. Notably, reversing the current trend in land degradation through agroforestry and reforestation of heavily degraded land using native legume trees provides substantial net benefits to Sudanese farmers and society alike. Concentrating on a 720,000 ha sized watershed in the southern Sudan, the impact of these restoration efforts on key provisioning and regulating ecosystem services was modelled, assuming that approximately 21 per cent of the existing agricultural land area would be dedicated to *A. Senegal* agroforestry and some 2 per cent (barren areas) to reforestation of drought tolerant *Boswellia* trees. A number of impressive findings result from this analysis, presented in the following and using a discount rate of 5 per cent for the PV estimates.

- Legume trees such as *A. Senegal* that are integrated within crop production systems at 6 x 6 m spacing can help contribute to enhanced soil moisture and soil nitrogen. These ecosystem services are estimated to provide an additional benefit of 10,000 SDG over a 25 year time horizon through their contribution to enhanced sorghum yields.
- The SWAT model that was estimated as part of this study demonstrates that sediment loss may be reduced by 500 kg/ha/yr, with each 500 kg containing an equivalent of 1 kg of inorganic NPK fertilizer. The avoided cost associated with replacing nutrient loss with inorganic fertilizers is 160 SDG/ha, assuming a constant fertilizer price.
- Additionally, *A. senegal* trees can be a source of valuable gum arabic. Using a conservative price estimate, we find a present value benefit to the individual farmer of 6,000 SDG/ha. This is equivalent to an annuity value of 436 SGD/ha/yr (75 USD/ha/yr) from gum arabic harvesting. At the end of the 25 year rotation, *A. senegal* trees may be cut and used for fuelwood, estimated to provide a present value benefit of 220 SDG (40 USD) worth of fuelwood per hectare (at 6 x 6 m spacing) subject to changes in shadow prices for fuelwood. Taking all these productive benefits together, the present value benefits to the farmer from integrating *A. senegal* trees in their agricultural production systems amounts to a yearly benefit stream of about 900 SDG/ha (160 USD/ha). This value is slightly lower for vertisol and slightly higher for clay loam soils.
- Taking into account private plantation and management costs associated with the agroforestry system, the annuity value of the present value of the future benefits to the farmer is estimated at 5,000 SGD/ha/yr to 1,000 SDG/ha/yr (90 - 180 USD/ha/yr), depending on the discount rate. The corresponding benefit cost ratio from investing in SLM is between 3 and 4. However, benefits to the farmer will not exceed costs until four years after the trees have been planted (*Figure 5*). As farmers in Geradef tend to be severely cash constrained and have higher internal discount rates than those used in this analysis, it is easy to understand why *A. senegal* agroforestry will not be adopted in the absence of adequate institutional support and economic incentives.
- The paper demonstrates that there is a strong case for supporting farmers in the adoption of agroforestry. In particular, substantial benefits will accrue to stakeholders within the

watershed as a whole. Reforestation of barren hilly land on 2 per cent of the surface area in combination with A. Senegal agroforestry on 21 per cent of farming land, will lead to approximately 37 m^3/ha/yr of additional infiltrated groundwater. This amounts to 4.5 million cubic meters for the watershed as a whole. Assuming that the increase in the shallow groundwater aquifers will replace the purchase of bottled water when water wholes run dry, the PV benefit of avoided water purchase is 20,000 SDG (3,500 USD) per hectare sustainably managed land, or 1,400 SDG/ha/yr (245 USD/ha/yr) in annuity value over the 25 years using a discount rate of 5 per cent.

- Finally, the SLM scenario will also result an additional 10 tonnes/ha/yr of below and above ground carbon sequestration. This analysis suggests that the avoided damage cost of such additional emissions to the global society is in the order of 28,200 SDG/ha for a discount rate of 5 per cent. Benefits associated with enhanced carbon sequestration are significantly higher for lower discount rates because most of the damages associated with carbon emissions are projected to incur in the future. All together, the societal benefit from implementing the proposed SLM scenario could be between 7 to 27 times larger than the costs to society, depending on the time value of money. Using a discount rate of 5 per cent, the NPV benefits of scaling up SLM practices on 123,000 hectares of land in Geradef amount to 7.3 billion SDG (1.3 billion USD) over the 25 year time horizon.

Conclusively, this analysis shows that although farmers can benefit significantly from the uptake of agroforestry and reforestation efforts on degraded lands and hills, there are positive externalities in production to the larger society within the watershed, who benefits substantially from enhanced ground water recharge, and to the global society, who benefits from carbon sequestration. Left on its own, the market fails to provide the necessary support to facilitate the uptake of SLM practices. There creates a case for helping create a favourable environment conducive to SLM investment via policy. One example could be subsidies for planting and managing *A. senegal* or other nitrogen fixating trees, at least in the first couple of years until the trees provide sufficient benefits to offset their management costs. Other regulatory or economic instruments that could help facilitate transition towards more sustainable land uses include access to credit at favourable rates, and the reinforcement of tree and land tenure security, especially for tenant farmers.

To lower costs associated with the proposed SLM scenario, experiences from the Western Sahel in Farmer Managed Natural Regeneration (FMNR[16]) could be examined as an alternative approach, whereby trees would be phased in more gradually and therefore at potentially lower cost (e.g., Haglund et al., 2011). However, natural regeneration may undermine the opportunities for continued mechanisation. Depending on the 'added value' of mechanisation versus traditional farming methods, the cost benefit outcome may be more or less favourable relative to the scenario evaluated in this report. This is an interesting and beneficial area of study for future research.

[16] FMNR is a low cost approach to sustainable land restoration especially used in drylands to support poor farmers increase the tree productivity without having to actively plant seedlings. FMNR can be adopted to restore the productivity of degraded croplands and grazing lands, as well as to restore degraded forests, thereby reversing biodiversity loss and reducing vulnerability to climate change.

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Appendices

Appendix A - Results from the household survey undertaken in Um Sagata – farm production characteristics

Variable	Mean (std. dev)	Variable	Mean (std. dev)
# of households	100	Grain sorghum yield in 2014 (kg/ha)	193 (161)
Age of household head	49 (14.1)	Heads of sheep owned	6.75 (28)
# of household members per household	8.5 (2)	Heads of goat owned	3.23 (19)
# of labourers per household	3.6 (0.7)	Heads of cow owned	1.5 (3.1)
Literacy of household head	35 %	Heads of donkey owned	0.3 (0.6)
Studies after primary school	30 %	Price of crop residue (straw) (SDG/kg)	0.18
Household head born in the same province	62 %	Price of Gum Arabic (SDG/kg)	7
Area of the farm (ha)	11 (22)	Price of firewood (SDG/m3)	35
% used for agriculture	92%	Price of water (SDG/m3)	42
% under fallow	5%		
% other uses (forest, pasture, etc.)	3%		

Appendix B - Results from the household survey undertaken in Um Sagata constraints to agroforestry

Fieldwork undertaken as part of this study has pointed to a number of constraint to the take up of agroforestry at the farm level. 100 farmers were asked to rate the following categories, if they perceived it as a very weak constraints (0) or very strong constraints (5). The relative rankings are provided, indicating the mean response and standard deviation (in brackets):

1) Lack of credit access: **3.68 (1.8)**

2) Lack of knowledge and extension services: **3.65 (1.88)**

3) Presence of trees that makes mechanized and drafted technical operation (seeding, tillage, etc.) more difficult: **2.87 (1.89)**

4) Free roaming livestock eating tree and scrub seedlings: **2.48 (1.9)**

5) Perceived loss of yields: **2.47 (1.87)**

6) Lack of irrigation schemes for the trees: **2.24 (1.78)**

7) Incomplete tenure security: **0.97 (1.07)**

Appendix C - Data inputs used for the AquaCrop analysis

The conceptual equation at the core of the AquaCrop growth engine[18] is

$$B = WP * \sum Tr \qquad \text{(Equation A.C1)}$$

, where B is produced biomass (above-ground), WP is water productivity (biomass per unit of cumulative transpiration), and $\sum Tr$ is the cumulative transpiration over the growth cycle.

The second core equation gives the relationship between the grain yield (Y) and the biomass produced:

$$Y = HI * B \qquad \text{(Equation A.C2)}$$

, where HI is the harvest index - the ratio of the grain weight over the total above-ground plant weight.

TABLE A.C1

Data inputs used for the SWAT analysis, which allowed for estimates of soil moisture levels

Variable	Land Use Scenario inputs	Source
Digital Elevation Modal	1325	USGS EROS Data Center (http://dads.create.usgs.gov/SRTM/) and National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA)
Soil	FAO Soil	FAO/UNESCO Soil Map of the World, FAO, 1971-81
Climate data	1990-2010 daily data	The National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalyses (CFSR) from Texas A&M University [http://globalweather.tamu.edu]
Software	ArcSWAT	ArcSWAT 2009.93.7b Texas A&M University [http://swat.tamu.edu/software/arcswat]

TABLE A.C2

Data inputs used to run the AquaCrop model

Type of data	Land Use Scenario inputs	Source
Climate data	1990-2010 daily data	The National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalyses (CFSR) from Texas A&M University [http://globalweather.tamu.edu]
Soil data	FAO Soil	FAO/UNESCO Soil Map of the World, FAO, 1971-81 and soil type-specific default values of AquaCrop
Crop data	AquaCrop model and literature	Most of the biophysical characteristics specific to the sorghum are already set in AquaCrop. For non-specified characteristics, values were found in the literature
Crop management data	Survey	Household survey taken in March 2014

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[18] *The readers who would like more information on FAO AquaCrop model are referred to the FAO website, where explanations and articles dedicated to the model are found (e.g., Steduto et al., 2008).*

Appendix D - Parameter estimates of the linear regression and ARMA model

To forecast the evolution of the sorghum price over 25 years, an Auto-Regressive Moving-Average (ARMA) model was used, which forms a class of linear time series models. Based on the real prices of sorghum (which are the deflated prices)[19] , the time-series observations were de-trended by regressing the prices over time and squared time, using a linear regression (OLS estimator) (*Equation A.D1)*. The (stationary) residuals of the linear regression were then used to estimate the parameters of the ARMA(1,1) model[20] , shown in *Equation A.D2.*

$$\widetilde{P}_t = \propto_0 + \propto_1 T + \propto_2 T^2 + Z_t \text{ With } T = 1991, 1992...2011. \qquad \text{(Equation A.D1)}$$

$$Z_t = \beta_1 Z_{t-1} + \theta_1 \bar{\epsilon}_{t-1} + \bar{\epsilon}_t \text{ With } \bar{\epsilon}_t \sim N\ (0.\sigma^2) \qquad \text{(Equation A.D2)}$$

, where $\widetilde{P}_t$ is the sorghum price in real term, *T* is time, and T² is the same variable squared. $\tilde{Z}_t$ represents the stationary residuals of the first equation (*A.C3*), and $\tilde{\epsilon}_t$ are the residuals of the ARMA model. The estimated parameters of the linear regression and ARMA regression are significant at 1 or 5 per cent levels and shown in *Table A.D1.*

TABLE A.D1

Parameter estimation of the linear regression and ARMA model

Parameters	Linear regression	Parameters	
$\propto_0$	132.01***	0.47**	
$\propto_1$	-13.62**	-0.99***	
$\propto_2$	1.13**		
Adjusted R² = 0.67		AIC = 211.1	

*** significant at the 1% level; ** significant at the 5% level.

Appendix E - Present value of enhanced nitrogen fixation and soil moisture

To estimate the PV of enhanced soil nitrogen and soil moisture:

$$PV_{\textit{additional nitrogen and soil moisture on sorghum yields}} = \sum_{t=0}^{24} \left[\frac{P_{t,g}(Q_{t,g,SLM} - Q_{t,g,baseline}) + P_{t,r}(Q_{t,r,SLM} - Q_{t,r,baseline})}{(1+r)^t} \right] \qquad \text{(Equation A.E1)}$$

, where $P_{t,g}$ the price of the grain sorghum at time t, $P_{t,r}$ the price of the crop residue at time *t*, $Q_{t,g,future}$ and $Q_{t,g,baseline}$ are sorghum yields at time t under the SLM and baseline scenarios, respectively, and $Q_{t,r,SLM}$ and $Q_{t,r,baseline}$ are crop residue yields at time *t* under the SLM and baseline scenarios, respectively. *r* is the discount rate and assumed to be equal to 5 per cent[21]. Results are given in *Table 5.*

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[19] *So that changes due to the inflation are not taken into account in the price forecast.*

[20] *In a ARMA(p,q) model, p is the order of the Autoregressive (AR) part and q the order of the Moving average (MA) part. Here, p = q = 1.*

[21] *In Chapter 9, the present values are given for two other values of the discount rate.*

Appendix F - Value of avoided soil erosion

As shown in *Table A.F1*, Myint (2014) demonstrates that soil erosion rates will be halved as a result of the SLM scenario. To subsequently assess the soil nitrogen content (*SNC*) in g/kg, authors need to know the bulk density (in g/cm^3) of the soil (*B*), as well as the depth (in m) of the soil (*D*). The weight of the soil (in kg/ha) can then be calculated as:

TABLE A.F1

Loss of soil in the baseline and SLM scenarios *(Myint, 2014)*

Scenario	Baseline	SLM
Annual sedimentation loss **(S)**	937 kg/ha	464 kg/ha

$$\textit{Weight of the soil} = 10\,000\,000 * D * B$$ (Equation A.F1)

, where $D = 0.2$ m and $B = 1.4$ g/cm^3. The values of *D* and *B* are derived from the soil analysis provided in Raddad (2006) and implemented in the clay soils of Sudan. The soil weight value obtained is 2,800,000 kg/ha. To evaluate the overall SNC, the nitrogen stock (NS) for a given area (NS, in kg/ha) can be used for a given area as follows:

$$SNC = \frac{NS}{weight\ of\ the\ soil}$$ (Equation A.F2)

, where *NS* = 900 000 g/ha (Raddad, 2006). Thus, *SNC* =0.321 g/kg. The quantity of phosphorus lost is also estimated ($Q_{phosphorus}$). Its estimation is easier as soil phosphorus content (*SPC*) is directly given in Raddad (2006) as *SPC*=0.393 g/kg. This allows for calculations of quantities of nitrogen and phosphorus carried off by soil erosion under the baseline scenario, which can be avoided under the SLM scenario:

$$Q_{nitrogen} = (S_{SLM} - S_{baseline}) * SNC$$ (Equation A.F3)

$$Q_{phosphorous} = (S_{SLM} - S_{baseline}) * SPC$$ (Equation A.F4)

$$PV_{avoided\ nutrient\ loss} = \sum_{t=0}^{24} \frac{\Delta nutrient\ loss * replacement\ cost}{(1+r)^t}$$ (Equation A.F5)

, where *Δnutrient loss* represent the amount of inorganic fertilizer needed to offset the loss of soil nitrogen and phosphorus between the baseline and SLM scenarios per hectare (1.09 kg), and the *replacement cost* is the price of fertilizers (10 SDG/kg according to the socio-economic survey).

Appendix G - Present value of gum arabic and fuelwood

The PV benefit of gum arabic production is simply that which is earned over and above the baseline scenario, according to *Equation A.G1:*

$$PV_{gum\ arabic} = \sum_{t=0}^{24} \left[\frac{P_{gum} * Q_{t,gum}}{(1+r)^t}\right]$$ (Equation A.G1)

, where *Pgum* is the price of gum arabic, and *Qt,gum* is the gum arabic yield at time *t*.

$$PV_{firewood} = \sum_{t=0}^{24} \left[\frac{+P_{fw} * Q_{t,fw}}{(1+r)^t}\right]$$

, where P_{fw} is the price of firewood, and $Q_{\ t,fw}$ the production of firewood per unit of land at time *t*.

The PV benefit of fuelwood is, according to the explanations in the text:

(Equation A.G2)

Appendix H - Present value of avoided purchase of potable water

The PV of enhanced shallow aquifer recharge over the 25 year time horizon is estimated according to *Equation A.H1* (where *r* is the discount rate assumed here to be equal to 5 per cent):

$$PV_{enhanced\ shallow\ aquifer\ recharge} = \sum_{t=0}^{24} \frac{\Delta\ in\ aquifer\ recharge_t * price\ of\ water}{(1+r)^t}$$

(Equation A.H1)

Appendix I - Carbon sequestration and storage

The total level of carbon dioxide stored within the watershed at any moment of time, is given by *Equation AI.1* and *AI.2*, as follows:

$$\Delta Carbon_{Tot} = \Delta Carbon_{AgF} + \Delta Carbon_{Boswellia} = Area_{AgF} * G_{AGF}(1+R) * CF + Area_{Boswellia} * G_{Boswellia}(1+R) * C$$

(Equation A.I1)

$$\Delta CO_{2\,Tot} = \Delta Carbon_{Tot} * \left(-\frac{44}{12}\right)$$

(Equation A.I2)

, where $Area_{AgF}$ and $Area_{Boswellia}$ are the surface under agroforestry and Boswellia tree cover *(B. catering, B. frererana,* and *B. papyrifera*). G_{AgF} and $G_{Boswellia}$ represent the annual average aboveground biomass increment related to 1 ha of *A. senegal* agroforestry system and 1 ha of Boswellia tree plantations respectively, *R* (= 0.48) is the ratio of belowground biomass to aboveground biomass (or root-to-shoot ratio), and *CF* (=0 .5) is the carbon fraction of dry matter to convert in tonnes of carbon. The two latter values are found in the IPCC report on good practices for land use (IPPC, 2003).

To estimate the annual average aboveground biomass increment, authors used the value provided in the IPCC report (2003) for tree plantations in climates in Africa with less than 1,000 mm of rain. The value of $G_{Boswellia}$ (annual average aboveground biomass increment related to 1 ha of Boswellia trees), is 15 tonnes of dry matter/ha/yr when the trees is 20 years old or younger and 11 tonnes of dry matter/ha/yr otherwise.

Furthermore, given that A. senegal is planted for agroforestry at a 6 x 6 m spacing (= 278 trees/ha) and not as a plantation, with a density 900 trees/ha, a corrector factor of 0.3 was thus used to measure the value of G_{AgF}. To convert tonnes of C to tonnes of CO_2, C is multiplied by a default conversion factor of 2.9 (44/15), (IPCC, 2003) as shown in *Equation A.I2*.

Appendix J: Present value economic benefit of enhanced carbon sequestration

SCC is combined with above derived changes in total carbon dioxide equivalent stocks, as a result of the SLM scenario, to estimate the PV of the additional carbon sequestered, as follows:

$$PV_{of\ additional\ carbon\ sequestred} = \sum_{t=0}^{24} \frac{SCC * \Delta CO_{2Total}}{(1+r)^t}$$

(Equation A.J1)

Appendix K - Net present value for the farmer associated with adoption of *A. senegal* agroforestry

NPV to the farmer associated with adoption of *A. senegal* agroforestry is given by *Equation A.K1*.

$$Net\ Present\ Value\ to\ the\ farmer = \sum_{t=0}^{24} \frac{Benefits\ (Land\ productivity)_{t,SLM}}{(1+r)^t} - \sum_{t=0}^{24} \frac{Benefits\ (Land\ productivity)_{t,baseline}}{(1+r)^t} - \left(\sum_{t=0}^{24} \frac{Costs_{t,SLM}}{(1+r)^t} - \sum_{t=0}^{24} \frac{Costs_{t,baseline}}{(1+r)^t}\right)$$

(Equation A.K1)

Appendix L - Assumptions of parameter distributions used in the Monte Carlo sensitivity analysis

TABLE A.L1

Assumptions regarding the distributions of gum arabic and firewood prices [22]

Price	Type of distribution	Mean	Standard deviation	Coefficient of variation	Sample size
gum arabic	Normal	7	2.1	30%	120 000 draws of 25 year time horizon
firewood	Normal	35	8	23%	

[22] *Given that authors did not have access to statistical series of prices, standard deviation is calculated so that minimum and maximal values are in the range stated by farmers.*

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