

Faculté des sciences

How could a carbon offset market system contribute to different agroforestry afforestation scenarios in Central Uganda? Assessment using carbon InVEST model

Auteur : Julie Hernandez

Promoteur·rices : Eric Lambin, Lina Tennhardt

Lecteur : Bas van Wesemael

Année académique : 2021-2022

Acknowledgements

I would like to thank warmly and acknowledge my supervisors, Eric Lambin and Lina Tennhardt, for the follow-up, help, enriching advice, and encouragement throughout the writing of my thesis. I would also like to mention and thank their great availability.

Thanks also to my former assistant, Raphaël, who spent few hours on some of my technical problems. You never really know if you are bothering him, because he always does it with a smile.

Thanks to my parents for the support and thorough proofreading, and to my sister Aurelia for the writing and academic tips.

Thanks to Dian Diang and Enzo for the unconditional entertaining encouragement and support.

Thanks to the other geography students, either being there from the beginning or who joined along the way, for the mutual support and the years spent hanging out in front of the Mercator at 3pm (and all that goes with it).

Thanks to my Erasmus spanish friends, Manuel, Guille, and Llorenç, who allowed me to discover geography from another (fun) point of view.

And finally, thanks to the little planet for supporting us.

Abstract

A fraction of the cumulative CO₂ emissions remains in the atmosphere, leading to global warming. One way to reduce CO₂ concentrations is to sequester the atmospheric carbon in trees and soils through plant. Agroforestry, defined as land use combining trees and crops, appears to be part of the solution, and has received increased attention due to its atmospheric carbon dioxide sequestration capacity. Cocoa production, which has a high global demand and is becoming increasingly important in Uganda, can typically take place in agroforestry schemes. This study focuses on a sample of cocoa farms located in Central Uganda (Mukono), and aims to assess the potential amounts of carbon that could be additionally stored if cocoa farmers convert their non-agroforestry land cover to agroforestry systems. Moreover, it evaluates the associated economic compensation that each farmer could receive for such a conversion. Results showed that conversion of short-cycle crop land to shaded agroforestry systems could result in an increase of 5.3% per unit area of the actual carbon stock. Farmers could receive US\$ 137.82 ha⁻¹ if the conversion to agroforestry is done in 20 years, and 1.5 times more if done in 5 years. Carbon storage benefits on a global scale, decreasing global warming, but also on a local scale to farmers, bringing several environmental and socioeconomic co-benefits.

Table of content

1	Introduction	1
2	Literature review	4
2.1	Cocoa production	4
2.1.1	World production	4
2.1.2	Case of Uganda	5
2.2	Ecosystem services	5
2.2.1	Definition	5
2.2.2	Payment for ecosystem services	5
2.2.3	Carbon offset market	6
2.3	Agroforestry	6
2.3.1	Environmental impacts	7
2.3.2	Socioeconomic impacts	10
2.4	Hypotheses of this study	11
3	Material and methods	13
3.1	Study area	13
3.2	Methodology	15
3.2.1	Land use classification	17
3.2.2	InVEST model parametrization	18
3.2.3	Intersection with a socioeconomic database	21
4	Results	22
4.1	LULC classification maps	22
4.1.1	Current (2019) situation: LULC classification map	22
4.1.2	Future situation: LULC classification map	23
4.2	Carbon storage and sequestration assessments through InVEST Model	24
4.2.1	Carbon pools	24
4.2.2	Current (2019) situation: carbon storage assessment	27
4.2.3	Future situation: carbon storage and sequestration assessments	28
4.2.4	Economic valuation	31
4.3	Valuation assessment per farm	31
4.3.1	Brief overview of the surveyed farms	31

4.3.2	Economic valuation per farm	32
4.3.3	Relation with cocoa production surface	35
5	Discussion	38
5.1	Classification map	38
5.2	Carbon storage assessment	39
5.2.1	Comparison with literature	39
5.2.2	Environmental impacts	40
5.3	Economic valuation assessment	41
5.3.1	Different time scale scenarios	41
5.3.2	Socioeconomic impacts	43
5.3.3	Integration of the economic valuation in the frame of an offset carbon market	44
5.4	Practical implementation constraints	46
5.5	Methodological reflection	48
6	Conclusion	50

Chapter 1

Introduction

Anthropogenic greenhouse gas (GHG) emissions, increasing continuously since the pre-industrial period and very likely to be among the causes of the current global warming, leads to severe perturbations of the natural systems, and to environmental, biological, and human damages and impacts. Therefore, the Intergovernmental Panel on Climate Change (IPCC) alerts policy makers on the severity of the impacts that a rise of even a tenth of Celsius degree at global scale may have, and recommends taking mitigation policies to reduce GHG emissions. In 2019, among the main different GHGs (CO_2 , CH_4 , NO_2), CO_2 represented up to 75% of the total emissions, coming mainly from fossil fuel combustion and industrial processes (IPCC, 2022c). Historical cumulative net CO_2 emissions from 1850 to 2019 amounts to 2400 ± 240 Gt CO_2 , the last decades having experienced the most intense emissions (IPCC, 2022c). A fraction is stored on terrestrial surfaces (soils and plants) and oceans, but the rest remains in the atmosphere (IPCC, 2007).

Climate change mitigation solutions do not consist in a single method, and it is more likely and realistic to consider a combination of several modest contributions (Albrecht and Kandji, 2003). Among those, one way to reduce CO_2 concentrations is to sequester the atmospheric carbon in trees and soils through plant respiration. Yet, primary forests surface area has a decreasing trend. Deforestation is mainly due to land shifting towards agriculture because of the increasing population which leads to land scarcity pressure. Therefore, agroforestry (land use combining trees and crops) appears to be part of the solution, and has received increased attention due to its atmospheric carbon dioxide sequestration capacity (Feliciano et al., 2018) at much more lower cost than through other CO_2 mitigating options (Albrecht and Kandji, 2003). Agroforestry can also be justified for many other reasons (Albrecht and Kandji, 2003), like environmental and socioeconomic co-benefits supply. In addition, increases in carbon stocks of agricultural systems can then poten-

tially be sold by farmers as CO₂ emission offsets in carbon offset markets (Luedeling et al., 2011). This mechanism can be of valuable consideration to incentivize smallholders, especially since they cannot afford a potential loss of income, sometimes already facing financial difficulties. But offsets need however to be considered in an integrated vision taking into account the associated costs and potential income losses in the balance.

The chocolate industry often faces negative reports concerning environmental and social issues in their supply chains (FiBL, 2022). Farmers worldwide have reduced the number of non-cocoa trees to increase short-term economic returns, thus converting shaded agroforestry systems to more intensive plantations (Middendorp et al., 2018). However, cocoa (*Theobroma cacao* L.) beans can typically grow in agroforestry systems, which is an alternative to intensive monoculture systems, as it is "a biodiversity-friendly way to produce food and guarantee economic returns, while sustaining ecosystem services" (Middendorp et al., 2018). The high global demand for chocolate (hence for cocoa) (Vaast and Somarriba, 2014) leads to a great potential for the adoption of sustainable practices and justifies the interest for the cocoa case.

Biophysically speaking, Africa's agricultural systems have potential for sequestering additional carbon (Luedeling et al., 2011). In Uganda, where cocoa production has become more and more important in recent decades (Jones and Gibbon, 2011), the organic agricultural sector is one of the most developed of Africa (Preissel and Reckling, 2010). However, Zhang et al. (2017) have assessed that total carbon stocks of Uganda have decreased of 29.1% from 2012 to 2017, mainly due to deforestation and forest degradation. In Central Uganda, most deforestation has been caused due to the high urban demand for charcoal, leading to unsustainable fuelwood production (Zhang et al., 2017).

Quantification of the carbon sequestration potential is a crucial process (Vaast and Somarriba, 2014). This study focuses on a sample of cocoa farms located in Central Uganda (Mukono), initially studied in the framework of a larger project led by the Research Institute of Organic Agriculture (FiBL). The general aim of their project is to identify how chocolate (and textile) supply chains can be made more sustainable (FiBL, 2022). For this purpose, they use real company cases, among which there is Schöki. This Swiss chocolate company wishes to improve the sustainability of their cocoa supply. The present thesis aims to assess the potential amounts of carbon that could be additionally stored if cocoa farmers (potential suppliers of Schöki) converted their non-agroforestry land cover to agroforestry systems. Moreover, it evaluates the associated economic compensation that each farmer could receive for such a conversion. The Carbon Storage and Sequestration InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model is

used for both assessments. Four agroforests implementation time scenarios are considered: short term and long term ones (5, 10, 15, and 20 years).

The work presented in this manuscript is structured as follows: Chapter 2 introduces the literature review and includes some of the key concepts discussed further. Chapter 3 describes the study area and details the applied methodology. The results are presented in Chapter 4 and discussed in Chapter 5 in the light of the literature review. Finally, Chapter 6 concludes the work.

Chapter 2

Literature review

2.1 Cocoa production

2.1.1 World production

Cocoa (*Theobroma cacao* L.) is mainly produced in tropical countries. According to the International Cocoa Organization (ICCO), during the cocoa year 2020/2021, 5226 thousand tons of cocoa were produced globally, of which 77.4% came from Africa, 17.8% from the Americas, and 4.8% from Asia and Oceania (ICCO, 2022). 80% of the cocoa production is estimated to come from 7 to 8 million small and family-managed farms all over the world, ranging in size around 0.25 to 5 ha, for whom it is essential to their livelihoods. Main importers of cocoa beans are Europe and North America (see Appendix, Fig. 1). However, cocoa production and commercialization is related to sustainability challenges and issues regarding a global demand exceeding supply (Nelson and Phillips, 2018; Vaast and Somarriba, 2014), because of its niche and ‘luxury’ status (Jones and Gibbon, 2011). In 2014, demand for cocoa was estimated to grow steadily at 1% annually (Vaast and Somarriba, 2014). Challenges concern both living and working conditions of the producers, and the deforestation that cocoa production has caused in recent decades (14-15 million ha of tropical forests, with around 10 million ha currently in production) (Vaast and Somarriba, 2014). Certification of production is a way to move towards sustainability. Certified area of cocoa production increased by 53.2% in average between 2015-2019, but decreased by 12.7% in the year 2018-2019 (FiBL, 2021). This gives a certified world production percentage of 22.7% (of which 20% by UTZ Rainforest Alliance) (FiBL, 2021).

2.1.2 Case of Uganda

The production of cocoa in Uganda started in the 1950s, but was relatively minimal until recently, out of step with the countries of the African West Coast. However, it has increased significantly, and has more than quadrupled between 2001 and 2009 ([Jones and Gibbon, 2011](#)). Cocoa represents 1.72% of the national exports, being in third position after gold and coffee. This equals to an export value for cocoa production of US\$ 101 million ([OEC, 2020](#)), which is about double compared to 2015 (US\$ 56.6 million) ([Gopaulchan et al., 2019](#)). The three main importing countries of Ugandan cocoa are Indonesia, Malaysia, and India ([OEC, 2020](#)). Uganda provides 6.8% of the total European Union (EU) cocoa beans import. By having 25.3% of its cocoa production under organic crop lands, it is the third exporter of organic cocoa into the EU ([GIZ, 2021](#)). Districts of major cocoa production in Uganda are Bundibugyo (Western Region) and Mukono (Central Region) ([Gopaulchan et al., 2019](#)).

2.2 Ecosystem services

2.2.1 Definition

Even if the term *ecosystem services* deserves deeper specification and clarification ([Danley and Widmark, 2016](#)), it can simply be defined as the "benefits people obtain from ecosystems" ([Millennium Ecosystem Assessment, 2005](#)). The Food and Agriculture Organization (FAO) recognizes four types of ecosystem services: provisioning (like food, raw materials, fresh water, and medicinal resources), regulating (local climate air quality, carbon sequestration and storage, moderation of extreme events, waste-water treatment, erosion prevention and maintenance of soil fertility, pollination, biological control, and regulation of water flow), supporting (habitat for species, maintenance of genetic diversity), and cultural services (recreation and mental and physical health, tourism, aesthetic appreciation and inspiration for culture, art, and sign, spiritual experience and sense of place) ([FAO, 2022](#)).

2.2.2 Payment for ecosystem services

Payments for ecosystem services (PES), whose implementation evolution is explained in detail by [Gómez-Baggethun et al. \(2010\)](#), is a concept that connects local land- and resource owners providing particular services (conservation or restoration of the ecosystem) with external beneficiaries (individuals, firms, or the public sector) to make direct, contractual, and conditional payments

for it (Dargains and Cabral, 2021; Millennium Ecosystem Assessment, 2005). Since their establishment, PES schemes have become a popular incentive tool for conservation and climate change mitigation worldwide and on different geographical scales (Dargains and Cabral, 2021).

2.2.3 Carbon offset market

Offsetting markets are a type of PES scheme allowing financial transactions for carbon offsetting that can either be voluntary or compliance-driven (Buckley Biggs et al., 2021). Carbon markets were born in the 2000s and today, carbon storage and sequestration in biomass and soils is one of the ecosystem services most included in market schemes (Gómez-Baggethun et al., 2010). Indeed, payments for carbon storage and sequestration (with the aim of compensating carbon emissions) is a well established PES, with a directly measurable character, at large commercial scale (Dargains and Cabral, 2021). Therefore, assessment studies of the economic valuation and potential of carbon storage and sequestration are needed beforehand. Farming practices leading to higher carbon storage, even if generating nonmarket benefits, may lead to smaller direct revenues for the smallholders. Therefore, additional carbon markets are essential to fill the gap by generating direct profits for service providers (Middendorp et al., 2018). Past experiences with offsetting schemes show that payments can give direct results: in 2012, when Ugandan farmers were paid for not cutting timber trees (US\$ 28 ha⁻¹ yr⁻¹), national deforestation rates were reduced by up to 9% (FAO and ICRAF, 2019; Jayachandran et al., 2017).

2.3 Agroforestry

Several definitions for the term *agroforestry* exist (Nair et al., 2009). For example, Dixon et al. (1994) describe it as a "land-use that involves deliberate retention, introduction or mixture of trees or other woody perennials in crop/annual production fields to benefit from the ecologic and economic interactions" and the FAO and ICRAF (2019) as the "land-use systems and technologies in which woody perennials (such as trees, shrubs, palms or bamboos) and agricultural crops or animals are deliberately grown on the same parcel of land in some form of spatial and temporal arrangement". However, there are several types and classification of agroforestry. Feliciano et al. (2018) for example, classified agroforestry in agrisilvicultural, silvopastoral, boundary planting, improved fallows, shadow, homegardens, and woodlots systems. Nair et al. (2009) considered shaded perennial, alley cropping, improved fallow, home gardens, tree intercropping and silvopastoral systems. The FAO (2015a) stated that agrisilvicultural, silvopastoral, and agrosilvopastoral are the main types of agroforestry systems.

Nair et al. (2009) assumed that 5% of the worldwide forests are agroforests, and therefore estimated the total area under agroforestry to 1023 million ha. There is an important remaining share of available lands that could be converted to agroforestry systems, and the quantification of the potential and services of these systems is crucial (Feliciano et al., 2018). However, Milder et al. (2015) reminded that some authors nuance this environmental-friendly practice and argue that the loss of those services by adopting intensive practices, can be compensated by the gain of other areas for nature conservation (concept of land sparing).

70% of the world cocoa production is estimated to be cultivated with various levels of shade (Vaast and Somarriba, 2014), which can be provided by agroforestry. It has been found in several cases that shaded agroforests yield less cocoa than full-sun monoculture cultivation (Middendorp et al., 2018; Tennhardt et al., 2022), at least on a short term (Vaast and Somarriba, 2014). Therefore, cocoa crops have been historically intensified to reach higher yields (Vaast and Somarriba, 2014). However, even if yields in agroforestry and organic systems can be lower than high-input agricultural systems, conversely, agroforestry can boost productivity and profit (depending on timeframe, socioeconomic, political and ecosystem context) (IPCC, 2022a). Cocoa grown in multi-strata agroforestry systems provide diversified livelihoods (to the farmers) and ecosystem services (both at local and global scale) (Vaast and Somarriba, 2014), which sometimes are not sufficiently addressed in studies assessing yield changes related to agroforestry systems conversion (Vaast and Somarriba, 2014) as they only consider cocoa yields and not the system yields. Because of the lack of markets for many of those ecosystem services, the economic value of agroforestry systems is largely underestimated (Middendorp et al., 2018).

2.3.1 Environmental impacts

Carbon storage and sequestration

Variation through time

Increasing attention has been paid to agroforestry because of its ability to sequester carbon dioxide from the atmosphere (Feliciano et al., 2018). Although, carbon sequestration is not constant through time (Nair et al., 2009): aboveground carbon sequestration rates vary from trees' planting to their equilibrium state. Feliciano et al. (2018) observed several phases during tree growing cycle as well as after, the length of which depends on several abiotic and biotic factors. (1) Establishment phase (< 5 years after planting) and (2) initial phase (between 5 and 10 years): both have high carbon sequestration, probably due to fast tree growth. (3) Full vigor phase (> 10 years): carbon sequestration rate is maintained for a few years, but tree growth slows down. (4) End of the full

vigor phase: carbon sequestration begins to decline, likely because of tree aging, respiration, and death, and because trees reach of maturity and equilibrium (carbon sequestration equaling carbon losses due to respiration) (Feliciano et al., 2018). Regarding the soil, it has limited potential to sequester carbon. Because of quasi-equilibrium sink saturation after a conversion to agroforestry systems, soil carbon decreases right away. It increases after an initial period (between 5 and 10 years), but then decreases again later on (> 15 years) (Feliciano et al., 2018). Initial land is furthermore highly important for the additional carbon stored in agroforests. In terms of beneficial systems for carbon storage, Nair et al. (2010) reports the following rank: forests $>$ agroforests $>$ tree plantations $>$ arable crops. If a primary forest is converted to agroforestry systems it will reduce the carbon stock. This was the case for example in Indonesia, where primary forests were converted to cocoa agroforests (Feliciano et al., 2018). Even if not mentioned in the rank, Dixon et al. (1994) also mentions the importance of wetlands preservation, because of the high content in soil carbon. However, Albrecht and Kandji (2003) reminded that what really matters and determines sequestration is the fate of the generated stocks afterwards. The type of agroforestry is of major importance, especially for aboveground sequestration. In sequential systems, if trees are harvested, part of the sequestered carbon will be released back into the atmosphere. Therefore, they stated that perennial agroforestry systems, allowing full tree growth, were realistically the only feasible way to store carbon in plant biomass, as sequestration does not have to end at wood harvest (Albrecht and Kandji, 2003).

Authors assessments

Assessment of agroforestry carbon storage and sequestration is a largely addressed topic in the literature, and varies highly between authors (see Appendix, Table 1). In addition to different methods, several environmental and farm management factors can also explain the differences in carbon stocks observed. First, factors related to the nature of the plant itself and plant characteristics: tree species, age, crops, biodiversity, tree density, and previous land use (Albrecht and Kandji, 2003; Feliciano et al., 2018; Nair et al., 2010), especially when considering sequestration. For the age, wood quality of species regarding their carbon accumulation rates remains an uncertainty: fast-growing species may accumulate more carbon than slow-growing species at the beginning of their cycle (e.g. first 10 years), but slow-growing species accumulate more carbon in the long term (Nair et al., 2010). Secondly, there are factors related to the system characteristics, such as: the structure, function, and stability (Albrecht and Kandji, 2003; Feliciano et al., 2018; Nair et al., 2010). The type of agroforestry also plays a crucial role in determining the amount of carbon storage and sequestration (Feliciano et al., 2018; Nair et al., 2010). Thirdly, management factors (Albrecht and Kandji, 2003; Nair et al., 2010), such as: tillage, fertilization, use of residues,

holding size, and harvesting regime (Feliciano et al., 2018). Fourthly, agro-ecological conditions of the region (Albrecht and Kandji, 2003) will affect the processes: altitude, climate, and wind (Feliciano et al., 2018). Finally, soil characteristics (Nair et al., 2010) and quality (Albrecht and Kandji, 2003), crucial because of the supporting role of the soil: structure, texture, fertility, and physical, chemical and biological conditions (Feliciano et al., 2018) such as organic matter and nutrients content (Nair et al., 2010).

However, Feliciano et al. (2018) insists on the importance of elaborating a full greenhouse gas emission budget to assess the potential of agroforestry systems in mitigation climate change, and not only focus on carbon. Other gases like methane and nitrous oxide should be taken into account as their processes in agroforestry systems may not be as beneficial as for carbon (Feliciano et al., 2018). Depending on the agroforestry type, practices like shifting cultivation, pasture maintenance burning, paddy cultivation, nitrogen fertilization, and animal production may favor the emission of other GHGs (Albrecht and Kandji, 2003).

Soil

Agroforestry systems enhance soil fertility (Albrecht and Kandji, 2003) and fertilization (Tschora and Cherubini, 2020), agricultural productivity and sustainability, nutrient cycling (Albrecht and Kandji, 2003), soil protection (Humphrey et al., 2017) against climate extremes (Tschora and Cherubini, 2020), and erosion control by the increment of the land cover (Albrecht and Kandji, 2003). Higher carbon storage also reduces the fire, the decomposition, the leaching and the erosion risks (Albrecht and Kandji, 2003).

Biodiversity

It seems that agroforestry plays an important role in biodiversity conservation. It can provide better connectivity between the forests remnants and small-scale shaded agroforestry systems which can stimulate the matrix quality for many species (Middendorp et al., 2018; Tschora and Cherubini, 2020), even if responses need some time after tree planting (Tschora and Cherubini, 2020). Also, shade trees provide an adaptive strategy to temperature rise lowering understory plant temperature (Tschora and Cherubini, 2020) and act as wind breakers (Ekesa et al., 2015). Furthermore, pollination largely determines cocoa yield (Claus et al., 2018). When cultivating cocoa in monoculture, the use of fertilizers and pesticides often increases. This leads to insect biodiversity decrease (at the expense of predators) and thus to pest outbreaks increase (Claus et al., 2018). Moreover, predominant cocoa pollinating midges require moist and decaying material to breed. Open and exposed to sunlight cocoa crops are thus less adequate (Claus et al., 2018). Therefore, agroforestry

appears as a wildlife-friendly alternative as it enhances pollination services by many group of species (Toledo-Hernández et al., 2017). The traditional managed type of agroforestry increases as well the presence of rare biological functional groups in comparison to monocultures, betadiversity of terrestrial plants, epiphytes, amphibians, and soil and litter invertebrates. Bats, birds, ants, soil fauna and mammals richness and diversity can also be increased by diversity and composition of cocoa plantation vegetation (Middendorp et al., 2018), like agroforestry. Shaded cacao agroforests are also less vulnerable to pests and herbivores, but depending on the shade and moisture level might be more subjective to fungal diseases (Rueda et al., 2018).

Pressure on forests

Agroforestry systems can have an impact on the remnants forests. According to Humphrey et al. (2017), agroforestry reduces the impacts on natural forests. However, according to Tschora and Cherubini (2020), even if agroforestry conversion is intended to reduce deforestation and forest degradation, whether pressure on forests is alleviated or not depends on socio- and macroeconomic factors.

Hydrological cycles

Water often being a limited element, agroforestry systems can benefit hydrological cycles: by its role in water regulation (Humphrey et al., 2017) and water yield (Vaast and Somarriba, 2014), by improving the hydraulic lift (Feliciano et al., 2018) and water infiltration, by protecting watersheds (Middendorp et al., 2018), and by reducing the evapotranspiration (Albrecht and Kandji, 2003) and water drought risks (Vaast and Somarriba, 2014). More specifically, as reported by Middendorp et al. (2018), some authors found that intermediate levels of canopy shade of 40 to 60% could protect cocoa trees from drought and could maintain high cocoa production.

2.3.2 Socioeconomic impacts

Increasing the agroforestry land cover could benefit smallholders on several social and economic aspects. First, it could allow them to diversify their farm products (Albrecht and Kandji, 2003) for sustaining livelihood diversification, which increases the resilience of households, their income diversification (Feliciano et al., 2018; Humphrey et al., 2017; Tschora and Cherubini, 2020), and food security and accessibility (Middendorp et al., 2018), thus safeguarding against financial risks (Feliciano et al., 2018). Agroforestry also plays a role in the reduction of the risk against price volatility. Gockowski et al. (2010) stated that "with a shaded system, when prices fall or illness

strikes, the farmer can reduce labor input or use of chemicals, without seriously affecting the future productive potential of the cocoa stock. Producers with full sun systems facing pressure from capsids and mistletoe do not have this option. If they do not spray, then their investment will be lost" (recalled by [Vaast and Somarriba \(2014\)](#)). Moreover, if the pesticide use is lower, it may also reduce health risk for farmers and workers, which an important social co-benefit ([Tennhardt et al., 2022](#)).

In addition, agroforestry can provide more firewood and timber resources ([Albrecht and Kandji, 2003](#)), which are highly valued by farmers, and fuelwood self-sufficiency ([Tschora and Cherubini, 2020](#)). These products can be consumed and/or sold, and alleviate pressure on forests at farm- and village-scale ([Tschora and Cherubini, 2020](#)). Agroforestry also safeguards farmers against biophysical risks (for example by the deeper roots improving hydraulic lift) ([Feliciano et al., 2018](#)). Presence of wild animal species could be increased: [Tschora and Cherubini \(2020\)](#) reported that Togo farmers noted an increase of rats and grasscutters, that can be hunted and eaten or sold as bushmeat, when switching to agroforestry.

In Africa and developing countries globally, social and cultural factors such as food security and rural development might have to be prioritized above climate change mitigation and carbon sequestration objectives due to the economic situation ([Feliciano et al., 2018](#); [Tschora and Cherubini, 2020](#)). [Tschora and Cherubini \(2020\)](#) stated that often there were trade-offs between productivity and high carbon sequestration rate, and recalled that this trade-off "underlines the conflicting goals of international policies for climate change mitigation and local farmers regarding agroforestry". They noted a win-win alternative situation considering plots with medium to high carbon stocks that seem to have good productivity; trade-offs would be minimized due to agroforestry and benefits would accrue both to the farms and the environment ([Tschora and Cherubini, 2020](#)).

Finally, the increase in carbon sequestration due to a conversion to agroforestry, offers smallholders the possibility to participate in carbon markets ([Middendorp et al., 2018](#)).

2.4 Hypotheses of this study

This brief literature review provided an overview of some of the topics covered in this thesis and background information for the hypotheses. Given the rank considered by [Nair et al. \(2010\)](#), conversion of short-cycle crop land to agroforestry systems should increase the carbon stock of smallholder farms. The storage of carbon in the soil should lead to increasing benefits for the farmers, both in terms of environmental aspects (e.g. increased soil quality) and economic aspects (e.g. diversification of incomes). With respect to the economic compensation valuation of carbon

sequestration, it can be expected that smallholder farmers could have financial benefits from participating in a carbon-offsetting scheme when converting their entire land to agroforestry systems. The literature review showed that conversion to agroforestry and the demonstration of an associated increase in carbon storage is a widely discussed topic. Nevertheless, the aim here is to apply the scheme to a specific sample of farms, in order to obtain a first estimate of the potential financial compensation.

Chapter 3

Material and methods

3.1 Study area

Uganda is located eastern Africa (1.3733° N, 32.2903° E), and borders South Sudan in the north, Kenya in the east, Rwanda and United Republic of Tanzania in the south and Democratic Republic of the Congo in the west. Its total area is 241 550 km², of which 37.8% is arable land, and although it is a landlocked country, 18% is open inland waters and wetlands (FAO, 2015b) (main water bodies being Lake Victoria, Lake Albert, Lake Kyoja, Lake Edward and Lake George) (FAO, 2014). The total national population is in grand expansion as it nearly doubled since 2000, reaching 45.741 million in 2020 (The World Bank, 2020). Population is mainly concentrated on the shores of Lakes Victoria, Albert, Edward, and George, and in 2013, 83.6% of the total population was rural (FAO, 2014).

Uganda's climate is equatorial with regional variations in annual temperatures and humidity. Mean temperatures range between 18°C and 35°C. Mean relative humidity ranges between 70 and 100%, which qualifies it as high. Mean annual rainfall is about 1180mm/year, but varies spatially ranging from 750mm/year in the northeast to 1500mm/year on the shores of Lake Victoria. In the southern part of the country two rainfall peaks occur between March-May and August-November, but no dry season is pronounced. Whereas in the northern part, one dry season occurs from November to March (FAO, 2014).

This study focuses on a region located in the central administrative region of Uganda, north-east of the capital Kampala, and more precisely part of the district of Mukono. Mukono is a district of Central Uganda including 3000km² of the Lake Victoria's surface at its south (added to other water bodies, Mukono has thus 3/4 of its surface under water) (Mukono District LG,

2015). It is characterized as a peri-urban district due to its relative proximity to Kampala (Ekesa et al., 2015), and counted 596 804 residents in 2014 (Uganda Bureau of Statistics, 2017). With 332 people/km² in 2014, the population density of the district is almost double the regional or national average of 175.7 and 174 people/km², respectively (Mukono District LG, 2015). The population is mainly young, with 52.1% aged between 0-17 years, and only 2.9% aged above 65 years. According to the Mukono District LG (2015), over 80% of the population is agricultural based. According to the Uganda Bureau of Statistics (2017), 66.7% of the population is engaged either in crop growing or livestock farming. And according to Ekesa et al. (2015), 59% is employed in agriculture (which is lower compared to other district's percentage (reaching up to 90%) and national average (66%) due to its urbanization rate (Ekesa et al., 2015)). There is a high market availability within and outside Mukono (Ekesa et al., 2015; Mukono District LG, 2015) for both crops and animal products (Uganda Bureau of Statistics, 2017) and the district is crossed by major highway linking Uganda to Kenya and national highway to north Uganda, which facilitates transportation and export transport of goods. However, high costs of agricultural inputs are opposed to low prices of agricultural outputs and there is high prevalence of pests and diseases (Mukono District LG, 2015). The district's production is affected by natural shocks such as coffee and banana wilt that has destroyed thousands of acres, added to economic shocks like price drops on the world market especially for coffee. Vanilla came up as a substitute crop for coffee but has then also experienced a price drop. All of this makes it difficult to maintain a stable economic agricultural life (Mukono District LG, 2015). Due the large water cover of the district, fishing is the third largest economic activity (Mukono District LG, 2015); note that the study area being located at the very opposite of Lake Victoria within the district, this activity may be less important there. Food most commonly consumed in Mukono is plantain, maize, rice, beans, cassava, fruits and vegetables (Ekesa et al., 2015). No reliable production data has been found at the district level, but Uganda's three main agricultural productions in 2020 were fruit, plantains and others, and roots and tubers (see Appendix, Table 2) (FAOSTAT, 2022). The topography is not very hilly or mountainous, ranging around 1000-1200m of altitude (Fig. 3.2). North Mukono (including study area) soils are mainly Nitrisols with Fluvisols in wetland zones, whereas Lake Victoria's surrounding crescent are Ferall-sols (Ekesa et al., 2015). The district's natural resources are described as lands, wetlands, fisheries, minerals, forest/trees, wildlife and biodiversity, rivers and lakes. It is estimated that 90% of its population depends directly on these for their livelihood and that everyone depends on it indirectly (Mukono District LG, 2015). However, high pressure is exerted on these resources (Ekesa et al., 2015; Mukono District LG, 2015) mainly due to high population growth, unsustainable agricultural practices, increasing demand for forest products, development processes, increasing dependence for economic returns, reducing settlement, and arable land (Mukono District LG, 2015).

The study area is located at the very north of the Mukono district and overflows on the Kayunga and Luwero districts. The total surface area amounts to 948km², and is cut diagonally at its south due to the satellite image. Lwajali River (coming from south-west of the study area) and Sezibwa River (coming from south-east) both border the sample of farms on each side. The two tributaries have their confluence point in the north, and become the Sezibwa River (heading to Lake Kyoga) (Fig. 3.1). The data of the sampled farms was collected within the framework of a larger project led by the Research Institute of Organic Agriculture (FiBL) and financed by the Swiss National Science Foundation within the framework of the National Research Plan 73 on Sustainable Economy. This project¹ started in 2018 and aims at studying sustainability mechanisms of Swiss chocolate companies along their supply chains. Within this project, data on farm-level sustainability indicators was collected on a random sample (205 among around 450 Ugandan cocoa farm smallholders in conversion to Organic certification) of the Swiss company's supplier base.

Mean surface area of the farms is 2.82 ± 2.96 ha. For the five past years, 49% of the farms were able to generate a positive net income (which also includes a living wage for the farmer and his family), 18% of the farms even surpassed them with a profit, but 33% of the farmers reported that the revenues did not cover the costs at all. 67% of the farms do not have other source of income² besides farming. The remaining 33% have in average 1.27 ± 0.57 other sources. In comparison with other crops, cocoa is the most important crop for 60% smallholders, the second most important for 27%, the third important for 9%, and the less important for 2%. 30% of the farm managers consider themselves committed to the principles of sustainability, 46% partly, and 23% do not consider themselves committed. Currently, no farm is selling products certified by a third-party certifier to carry an eco-label.

3.2 Methodology

In this study, I applied three successive methodological approaches. First, I developed a current land use classification map of the study area in order to assess the carbon storage. Secondly, I parametrized and ran the InVEST model for the current land use land cover (which outputs the carbon storage) and for four different implementation time scenarios (which outputs the carbon sequestration and the associated economic valuation). Finally, I integrated the outputs of the model with a socioeconomic database of a sample of cocoa farm smallholders in order to better

¹Project title: *Enhancing supply chain stability, resilience and sustainability through improved sub-supplier management – chocolate and cotton apparel case studies.*

<https://www.fibl.org/en/themes/projectdatabase/projectitem/project/1478>

²Related to agriculture and which contribute more than 10% of farmer's income

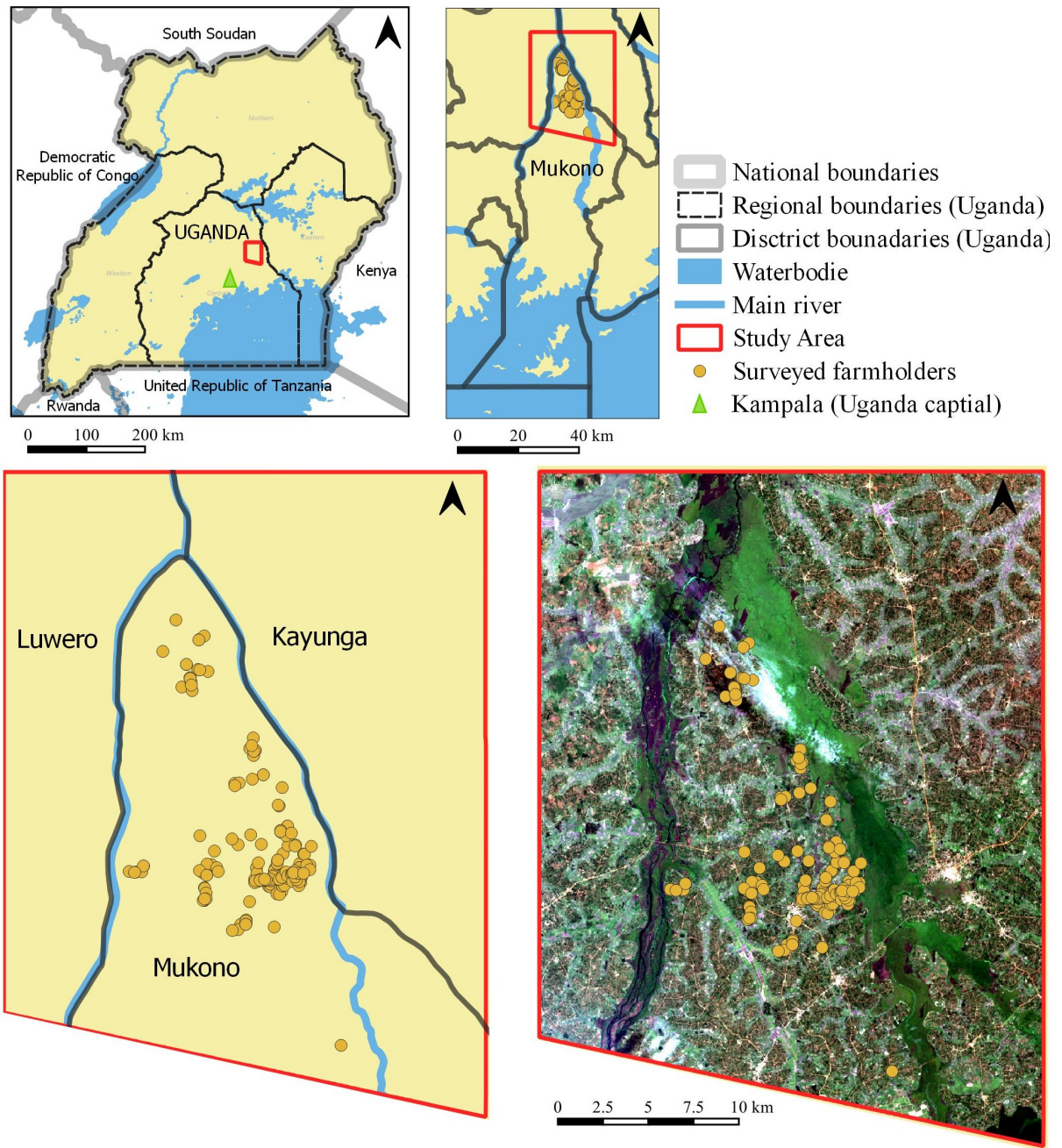


Figure 3.1: Study area (represented by a red polygon). Main river and district information in the lower left section, and real colors Landsat 8 (band 4,3,2) image (March 2019) in the lower right section. Location of the study area in Uganda upper left section and in Mukono District upper right section. Data sources: Landsat 8 image (United States Geological Survey Earthexplorer portal); Sampled smallholders (Tennhardt, 2022).

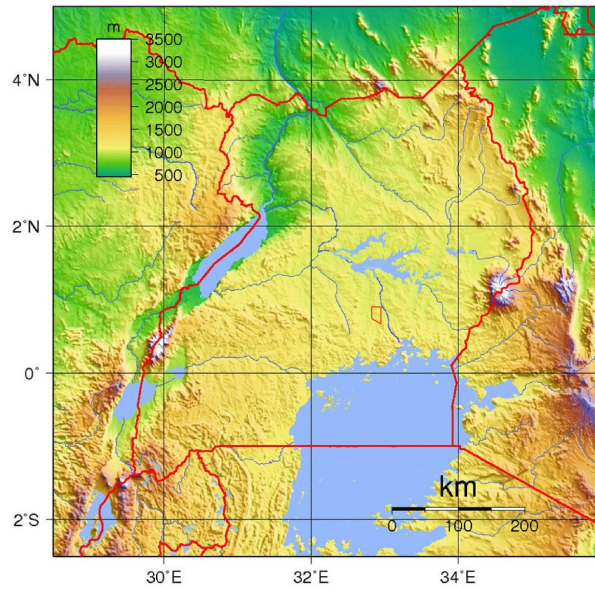


Figure 3.2: Detailed topographical map of Uganda. Study area represented by a red polygon inside Uganda's limits. Source: Maplands, s.d.

reflect the reality of the field.

3.2.1 Land use classification

The purpose of this section was to obtain a simplified current classification map of the study area, as it was one of the major needed inputs in order to run the carbon InVEST model (next section). The classification has been done on the basis of a Landsat-8 satellite image. The chosen satellite image was taken 10th March 2019, as March corresponds to the transition between a dry and humid period of the year which facilitates visual differentiation between land use types, and because of the little to non-existent cloud cover of the image. This data can be downloaded from the United States Geological Survey Earthexplorer portal. In order to obtain the land use classification map, I used a supervised classification with a maximum likelihood algorithm criteria. I considered four major classes: vegetated wetlands (i.e. vegetated lands impacted by wetlands on which there is no agricultural activity), non-vegetated wetlands (i.e. non-vegetated lands impacted by wetlands on which there is no agricultural activity), classical agricultural systems (i.e. mainly short-cycle crops for staple food production), and agroforestry systems (i.e. association of trees and crops or livestock to obtain products or services useful to humans). Several trials were made, comparing the integration of all spectral bands (i.e. the 11 bands) or a selection of bands (i.e. bands 2, 3, 4, 5, 6, 7, and 9) to the classification. I established the delimitation and determination of the

training samples visualizing remote sensing indices (wetness, brightness, greenness, NDVI, and different band compositions such as false color infrared) as well as pictures directly taken in the field of the study area (photographer: Mwesigwa Lauben, 2021). I applied a majority filter on the final classification to refine it, setting the used number of neighbors to *height* and the replacement threshold to *half*. Finally, I calculated a Cohen’s Kappa coefficient (κ) to assess the validation of the classification. 127 random verification points have been generated across the area, and training samples have been increased until obtaining $\kappa > 0.8$.

3.2.2 InVEST model parametrization

The InVEST suite models

The model I used in this study comes from the InVEST suite models (Integrated Valuation of Ecosystem Services and Tradeoffs), developed by the Natural Capital Project of Stanford University. InVEST is a suite of 18 open-source models that enables the assessment, the valuation, and the mapping of several ecosystem services. As trade-offs among natural resources are common, InVEST can constitute a tool for decision makers in order to assess them and to identify where investments in the enhancement of ecosystem services are most beneficial and necessary (Project, 2019). In this study, I used the Carbon Storage and Sequestration model; carbon storage and sequestration being a regulating service provided by nature to the world and its population.

The Carbon Storage and Sequestration InVEST model

This model estimates the amount of carbon currently stored in a given area. If a future land use scenario is given, it also estimates the amount of the additional sequestered carbon in that period of time. If a sequestration estimation is done, an economic valuation of the sequestered (or released) carbon can also be integrated, which outputs the economic value of the sequestered (or released) carbon between the current and the future landscape dates. This functionality can be very useful to estimate the value of the ecosystem service to society.

The model requires a current LULC (Land Use Land Cover) map of the study area and a table of the different carbon pools (aboveground biomass, belowground biomass, soil and dead organic matter, and in some cases litter and harvested wood) currently stored. If sequestration is estimated, it additionally requires future LULC map and the calendar year of both input maps (current and future). If the economic valuation of the additional stored carbon is estimated, it additionally requires the price per metric ton of carbon, the annual market discount on the price of carbon in %, and the annual rate of change in price of carbon in %.

Parametrization of the Carbon Storage and Sequestration InVEST model

LULC current classification and scenarios

The current (2019) LULC map used is the one detailed in section 3.2.1. A future LULC map was made assuming that all cells of classical agricultural systems from the current LULC were converted to agroforestry systems, and has been used for the four implementation time scenarios. The parameter changing in the scenarios is the future LULC calendar year. It defines the estimated time to operate the conversion from classical agricultural systems to agroforestry systems, following the procedure. Future calendar years have been set, respectively for the four scenarios to: 2024 (5 years shift), 2029 (10 years shift), 2034 (15 years shift) and 2039 (20 years shift), assuming several implementation cases (from soft to harder engineering).

Carbon pools

For the sake of simplicity and coherence and due to the available data, I focused on aboveground biomass and soil organic carbon. Both data have been extracted from Global Forest Watch portal. The aboveground biomass corresponds to the Tree Biomass Density layer (Harris et al., 2021) which identifies the aboveground live woody biomass density at a 30m resolution. Given that the input carbon pools were necessary in carbon units, the values of this layer have been divided by two (approximate conversion from biomass to carbon content) (Nair et al., 2010). The soil organic matter corresponds to the Soil Carbon Density layer (Sanderman et al., 2018) which identifies organic carbon density in the topsoil (0-30 cm depth) supposedly at a 30m resolution. However, once downloaded, the grid cell resolution appeared to be 250m instead of 30m for the Soil Carbon Density layer. I extracted mean values of both carbon pools layers for each (4) class of the current LULC through a zonal statistic extraction (ArcMap 10.6). The missing carbon pools have been set to zero, and thus did not account into the model.

According to Liang et al. (2017), the InVEST model uses Equ. (3.1) in order to calculate the carbon storage $C_{m,i,j}$ for a given cell grid (i, j) with the land-use type m ; A representing the actual area of each grid cell, $C(a, b, s, d)_{m,i,j}$ representing the densities of the carbon pools (aboveground carbon density, belowground carbon density, soil organic carbon density and dead organic matter carbon density) (in Mg C ha^{-1}) for grid cell (i, j) with land-use type m . Note that $Cb_{m,i,j}$ and $Cdm_{i,j}$ were set to zero. Thus, for the entire region, carbon storage C can be calculated as in Equ. (3.2) and carbon sequestration S between two given years as in Equ. (3.3); C^{T2} and C^{T1} representing the carbon storage in years $T2$ and $T1$ ($T2 > T1$), respectively

$$C_{m,i,j} = A \times (Ca_{m,i,j} + Cb_{m,i,j} + Cs_{m,i,j} + Cd_{m,i,j}) \quad (3.1)$$

$$C = \sum_{m=1}^n C_{m,i,j} \quad (3.2)$$

$$S = C^{T2} - C^{T1} \quad (3.3)$$

The valuation

I chose the social cost of carbon (SCC) as referent for the price/metric ton of carbon, as recommended by the InVEST model. Generally speaking, the social cost of a greenhouse gas (SC-GHG) is *the monetary value of the net harm to society associated with adding a small amount of that GHG to the atmosphere in a given year. In principle, it includes the value of all climate change impacts, including (but not limited to) changes in net agricultural productivity, human health effects, property damage from increased flood risk natural disasters, disruption of energy systems, risk of conflict, environmental migration, and the value of ecosystem services. The SC-GHG, therefore, should reflect the societal value of reducing emissions of the gas in question by one metric ton* (IWG, 2021). More precisely, the SCC can be defined as an estimate of the economic and social value of the emission of an extra ton of carbon in the atmosphere (in carbon dioxide) (IPCC, 2007) or as the social damage avoided by not releasing that ton of carbon (IPCC, 2007; Natural Capital Project, sd). The SCC value varies depending on the authors and time: Wang et al. (2019) estimated SCC to range from -13.36 to 2386.91 US\$/tCO₂, with a mean value of 54.70 US\$/tCO₂. I selected a SCC value of 51 US\$/tCO₂, as mentioned by the Interagency Working Group on Social Cost of Greenhouse Gases, at an annual market discount rate of 3% (IWG, 2021). The annual market discount rate represents the preference society has for immediate benefits towards future benefits. A higher value of the annual market discount reflects a higher preference for immediate benefits, and thus reduces the value of the sequestration of carbon over time. Regarding the annual rate of change in price of carbon, it adjusts the value of carbon sequestration over time, reflecting the greater climatic (and thus social) impact of carbon sequestered immediately over carbon sequestered in the future. If believed and expected that carbon sequestration today has more impact on climate change mitigation than the sequestration of the same amount in the future, then the annual rate of change in price of carbon should be set positively. Inversely, it should be set negatively (Natural Capital Project, sd). A higher value reduces the value of sequestration over time. I chose an annual rate of change in price of carbon of 3%, as suggested by Nordhaus (2017).

The equation of the economic valuation of carbon sequestration (S) used by the InVEST Natural Capital Project for a given area over a certain period of time is given in Equ. (3.4), where V

represents the price per metric ton of carbon, S_x the amount of carbon in metric tons sequestered on parcel x , q the future year, p the current year, r the yearly market discount rate for the carbon price, and c the yearly rate of change in the price of carbon.

$$S \text{ economic valuation } (Sev) = V \frac{S_x}{q-p} \sum_{t=0}^{q-p-1} \frac{1}{(1 + \frac{r}{100})^t (1 + \frac{c}{100})^t} \quad (3.4)$$

3.2.3 Intersection with a socioeconomic database

The purpose is to cross the values of the sequestered carbon obtained by the model (values per cell of 30m²) with data of the sampled farms. Indeed, the carbon pools extraction and the assessment of carbon storage has been made on the basis of the average of the whole study area for better accuracy. However, a landscape analysis of the economic valuation of the additional carbon storage would be arbitrary and meaningless in this case, given that the total study area has been broadened arbitrarily. The aim is to estimate the economic income through carbon sequestration for each farm of the sample if they converted all their crop land into agroforestry. Therefore, I first converted the value of sequestered carbon obtained from the InVEST model from US\$ cell⁻¹ to US\$ ha⁻¹. Secondly, I extracted the non-agroforestry area of each sampled farm and calculated the value of sequestered carbon if this area was converted agroforestry. Using Equ. (3.5), it gives an economic valuation for a given scenario for each farm; Sev being the economic value of sequestration for a given scenario³ which is multiplied by a factor⁴ in order to pass from cell units to hectare units, TFA being the Total Farm Area⁵, and AA the Agroforestry Area of the farm⁵. Final results have been expressed in total economic valuation between the two calendar years of the given scenario (as it is in the InVEST model's output) and have also been expressed per year and per month. This method has the advantage of being more realistic and of giving results able to be incorporated in hypothetical carbon offset markets. In addition to providing area data, the database also allowed for the analysis of several socioeconomic indicators of the sample, which can subsequently be compared with literature.

$$\frac{US\$}{farm} = (Sev \times 0.08989546027) \times (TFA - AA) \quad (3.5)$$

³Obtained by the InVEST model as indicated Equ. (3.4)

⁴Coming from the cell resolution of the output being 29.98257165m, which gives a cell surface of 898.9546027m² or 0.08989546027 hectares (desired unit)

⁵Obtained from the database (Tennhardt, 2022)

Chapter 4

Results

4.1 LULC classification maps

4.1.1 Current (2019) situation: LULC classification map

With a k (Cohen's Kappa) coefficient of 0.8217, the LULC map including all spectral bands had a greater accuracy than the case including a selection of bands ($k = 0.7548$). Classical agricultural systems had the highest omission error with a rate of 0.25 (Table 4.1). The classification revealed clear spatial patterns between agroforestry systems, classical agricultural systems, vegetated wetlands, and non-vegetated wetlands (Fig. 4.1). The major land cover in terms of surface in the study area corresponds to the agroforestry system class with 46% of the total area, followed by the classical agricultural systems with 32%, the wetlands with 18%, and the non-vegetated wetlands with 4%. Water (two main rivers appearing in Fig. 3.1) has not been represented for the sake of simplicity, but coincides with wetlands.

Table 4.1: Accuracy assessment results from the current LULC classification map.

LULC	Verif. points	Omission error	Commission error	Classes accuracy
Wetlands	21	0.0952	0.1739	0.9048
Non-vegetated wetlands	20	0.05	0.1364	0.95
Agroforestry systems	54	0.0926	0.0926	0.9074
Classical agri- cultural systems	32	0.25	0.1429	0.75
Overall accuracy : 0.8740				
Kappa coefficient : 0.8217				

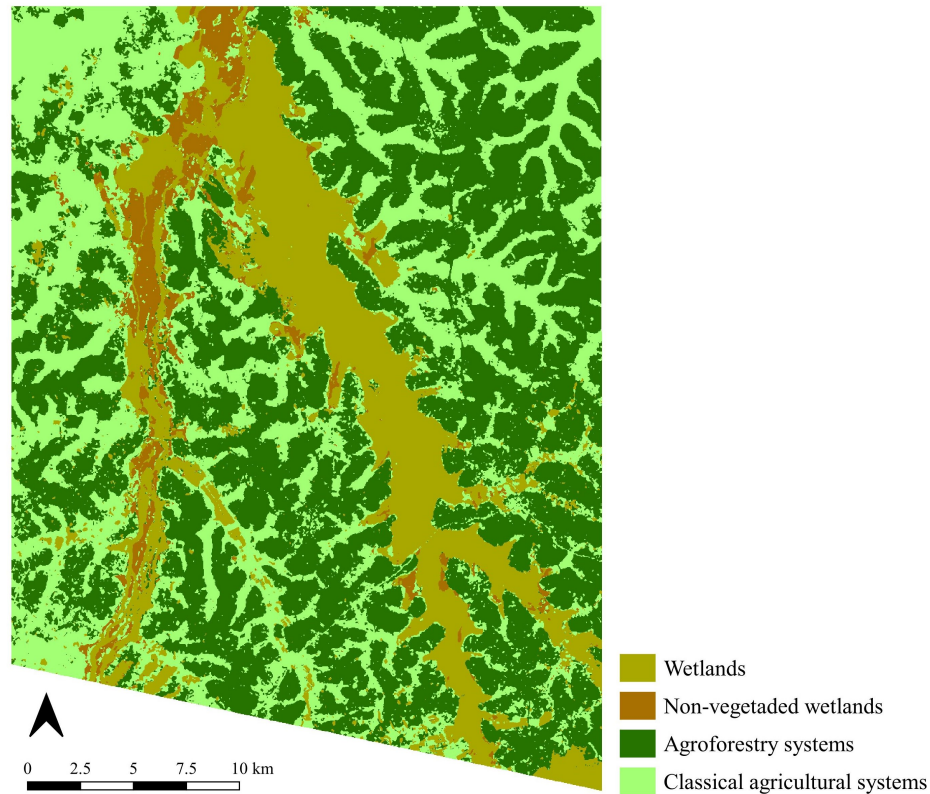


Figure 4.1: Land Use Land Cover classification map, based on 2019 Landsat 8 image.

4.1.2 Future situation: LULC classification map

As an extreme future landscape situation of the study area, all classical agricultural systems from the current LULC have been converted to agroforestry systems, without taking into account any environmental (topography, soil-type, soil moisture, ecological niches, etc) or social constraints. In this situation, the landscape is dominated by agroforestry systems, representing 78% of the study area. Wetlands and non-vegetated wetlands remain unchanged, thus corresponding to 18% and 4% of the study area, respectively (Fig. 4.2).

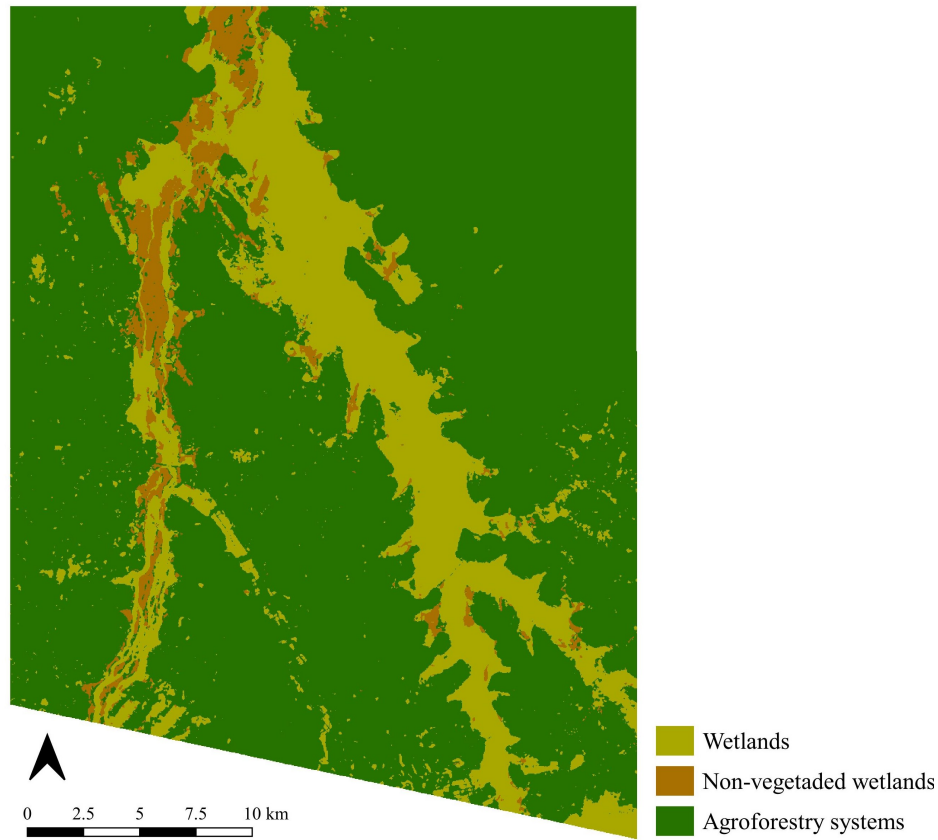


Figure 4.2: Hypothetical extreme future Land Use Land Cover classification map. Calendar year to reach it varies through the scenarios, respectively being 2024, 2029, 2034 and 2039.

4.2 Carbon storage and sequestration assessments through InVEST Model

4.2.1 Carbon pools

The zonal statistics extraction represented in Table 4.2 indicates the carbon values extracted by class from the Tree Biomass Density layer ([Harris et al., 2021](#)) and the Soil Carbon Density layer ([Sanderman et al., 2018](#)). In general terms, wetlands had higher carbon content (in both pools), followed by the non-vegetated wetlands, the agroforestry systems, and finally the classical agricultural systems. To test for significant difference in the carbon pool values, I generated random point samples across each class, from which I extracted carbon pool values. For all classes, aboveground carbon density had higher standard deviation and more outliers than soil organic carbon (Fig. 4.3). As tests of difference in means, I used Wilcoxon tests because the majority of the extracted data

was not normally distributed (required condition for Student tests). Considering a significance threshold α of 0.05, all combinations differed significantly, except agroforestry systems/classical agricultural systems for the soil organic carbon ($p=0.6055$) and wetlands/non-vegetated wetlands for the aboveground biomass carbon ($p=0.1008$) (Table 4.3).

Only mean values of the extraction (bold in Table 4.2) were used to build up the carbon pools input table for the InVEST model, as single values are required. However, it is important to keep in mind that there is a large variance. Carbon density of belowground biomass and carbon density of soil have both been set to 0 (Table 4.4).

Table 4.2: Main statistics of the carbon pools storage value extraction by LULC class expressed in MgC ha^{-1} and area (in ha) of each LULC class. AGB = aboveground biomass.

	Area (ha)	AGB carbon density				Soil organic carbon			
		<i>Min</i>	<i>Max</i>	<i>Mean</i>	<i>Std</i>	<i>Min</i>	<i>Max</i>	<i>Mean</i>	<i>Std</i>
Wetlands	17424.26	2	178.5	44.19	19.82	49	70	58.83	3.51
Non-vegetated wetlands	3792.87	11.5	151.5	40.17	11.92	52	69	58.12	2.89
Agroforestry systems	43541.05	1	172.5	32.13	13.08	48	71	56.49	3.12
Classical agricultural systems	29942.74	1.5	164	27.74	13.3	47	70	56.41	3.28
Total	94700.91								

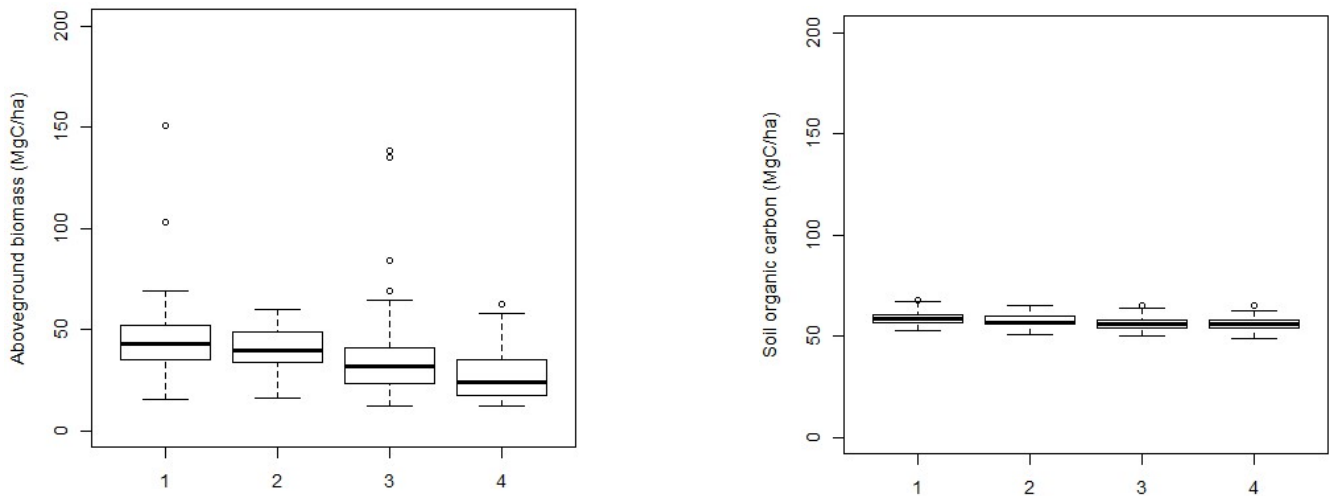


Figure 4.3: Boxplots of the extraction carbon pool values for each class. Aboveground biomass on the left and soil organic carbon on the right. 1 = vegetated wetlands, 2 = non-vegetated wetlands, 3 = agroforestry systems, 4 = classical agricultural systems.

Table 4.3: Wilcoxon test statistics for each combination, and its associated p -values. $H_0 : \mu_1 = \mu_2$.
* = significance considering $\alpha = 0.05$.

	Soil Organic Carbon							
	Wetlands		Non-vegetated wetlands		Agroforestry systems		Classical agricultural systems	
	w	p -val	w	p -val	w	p -val	w	p -val
Wetlands	-							
Non-vegetated wetlands	5504	0.008593*	-					
Agroforestry systems	12822	8.079e-10*	6984.5	0.002167*	-			
Classical agricultural systems	13177	4.83e-11*	7220	0.0004956*	11560	0.6055	-	

	Aboveground Biomass Carbon							
	Wetlands		Non-vegetated wetlands		Agroforestry systems		Classical agricultural systems	
	w	p -val	w	p -val	w	p -val	w	p -val
Wetlands	-							
Non-vegetated wetlands	5129.5	0.1008	-					
Agroforestry systems	13047	2.191e-10*	7582.5	2.118e-05*	-			
Classical agricultural systems	14810	2.2e-16*	8863.5	1.982e-12*	14482	1.687e-05*	-	

Table 4.4: Carbon pools input table required by the InVEST model, expressed in MgC ha^{-1} .
C_above = carbon density of aboveground biomass ; C_below = carbon density of belowground biomass ; C_soil = carbon density of soil ; C_dead = carbon density of dead matter.

lucode	LULC_name	C_above	C_below	C_soil	C_dead
1	Wetlands	44.19	0	58.83	0
2	Non-vegetated wetlands	40.17	0	58.12	0
3	Agroforestry systems	32.13	0	56.49	0
4	Classical agricultural systems	27.74	0	56.41	0

4.2.2 Current (2019) situation: carbon storage assessment

The study area's current stock of carbon is given by the InVEST model in the form of a map. The initial values of the output were given into MgC by pixel, but have been converted here in MgC ha^{-1} for better comparison (Fig. 4.4). Total carbon storage per unit area is the sum of the aboveground carbon density mean and the soil organic carbon mean. Thus, regarding the values of Table 4.4 and the output map (Fig. 4.4), the wetlands had the largest total amounts of carbon stock (average of $103.02 \text{ MgC ha}^{-1}$), followed by the non-vegetated wetlands, the agroforestry systems, and finally the classical agricultural systems. The total value of the stock of carbon for the whole area was estimated to $8\,546\,642.33 \text{ MgC}$.

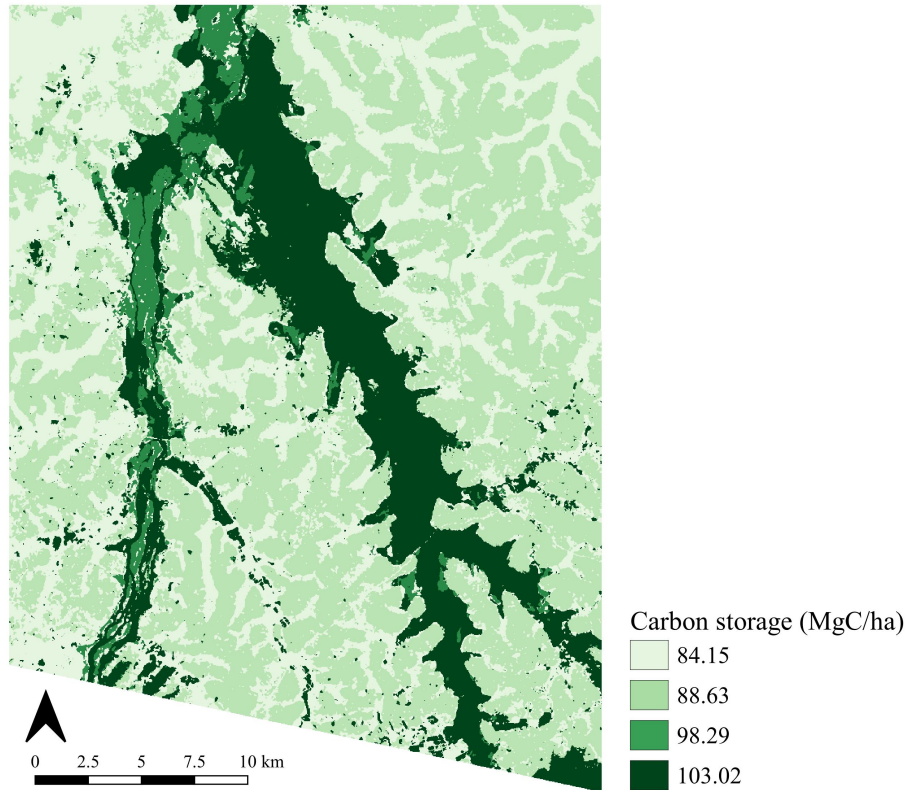


Figure 4.4: Map of the current (2019) carbon storage of the study area assessed by the InVEST model. Units are in MgC ha^{-1} .

Table 4.5: InVEST model’s estimation of the stored carbon values per class for the current situation. Units are in MgC ha⁻¹ (except for the total stored carbon of the whole study area).

	Current LULC		
	AGB	Soil	Total
Wetlands	44.19	58.83	103.02
Non-vegetated wetlands	40.17	58.12	98.29
Agroforestry systems	32.13	56.49	88.63
Classical agricultural systems	27.74	56.41	84.15
Total stored carbon : 8 546 642.33 MgC			

4.2.3 Future situation: carbon storage and sequestration assessments

Once all classical agricultural system cells have been converted by simulation to agroforestry system cells, InVEST outputs a map of the future carbon stock (Fig. 4.5). Carbon stock values per unit area respectively to each class were the same as for the current carbon storage map. Given the changes in proportion, the total carbon stock value for the whole study area increased to 8 680 606.50 MgC. Net difference between the current and future carbon stock situations was thus 133 964.71 MgC for the whole study area. The only class that sequestered additional carbon due to the change applied was the classical agricultural systems (of the current situation), resulting in an increase of 4.47 MgC ha⁻¹ (Fig. 4.6). It corresponds to the *Delta* in MgC ha⁻¹ between the current and future situation (Table 4.6). Major contribution comes from the sequestration in the aboveground biomass (4.39192 MgC ha⁻¹) compared to the soil (0.08211 MgC ha⁻¹). The net *Delta* does not vary among the different scenarios as the same current and future situations LULC maps have been given for all of them (Figs.4.1 and 4.2). This corresponds to the potential additional carbon storage generated by a conversion to agroforestry compared to a situation where nothing would have been changed. Among the 205 sampled farms, a total of 243.26 ha could be potentially converted to agroforestry. Thus, integrated to the farms, a total amount of 1087.3 MgC could be potentially additionally stored. If we assume that such a change does not happen instantly but progressively, we can formulate scenarios in time and assess the additional carbon storage value that would be added on an ongoing basis until reaching the final net total *Delta* value. The progressions are faster for shorter time scenarios, and slower for longer time scenarios (Table 4.7); relations are assumed here in a linear way.

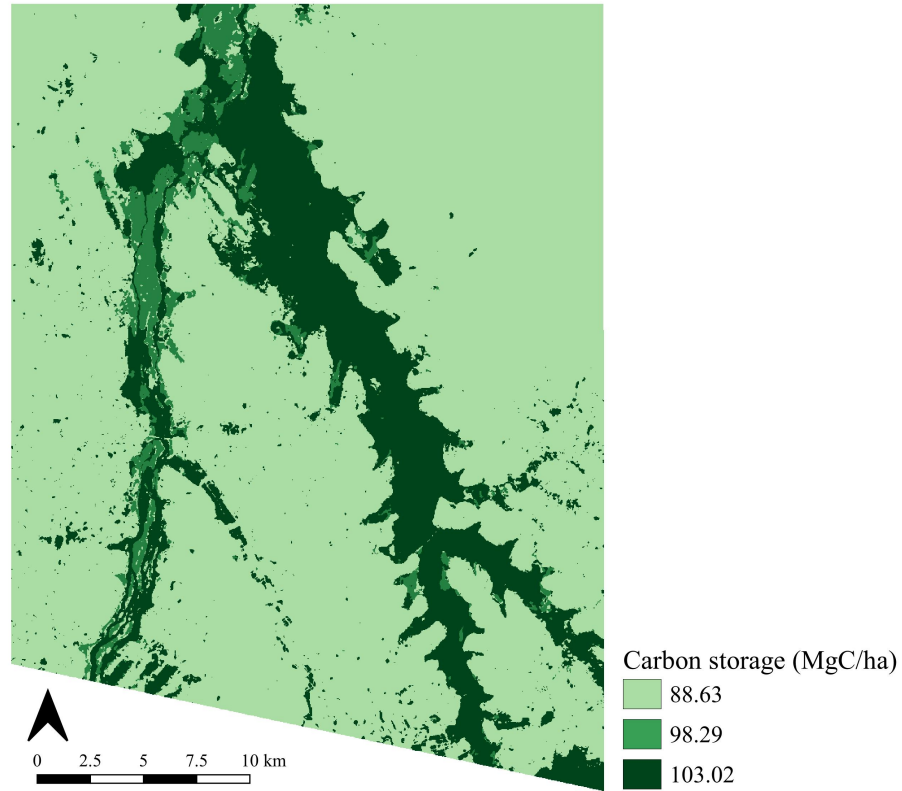


Figure 4.5: Map of the future situation carbon storage of the study area assessed by the InVEST model. Units are in MgC ha^{-1} .

Table 4.6: InVEST model's estimation of the stored carbon values per class for the future situation. Units are in MgC ha^{-1} (except for the total stored carbon of the whole study area and the net difference).

	Future LULC			Delta
	AGB	Soil	Total	(total)
Wetlands	44.19	58.83	103.02	0
Non-vegetated wetlands	40.17	58.12	98.29	0
Agroforestry systems	32.13	56.49	88.63	0
Classical agricultural systems	32.13	56.49	88.63	4.47
Total stored carbon : 8 680 606.50 MgC				
Net difference with current situation : 133 964.71 MgC				

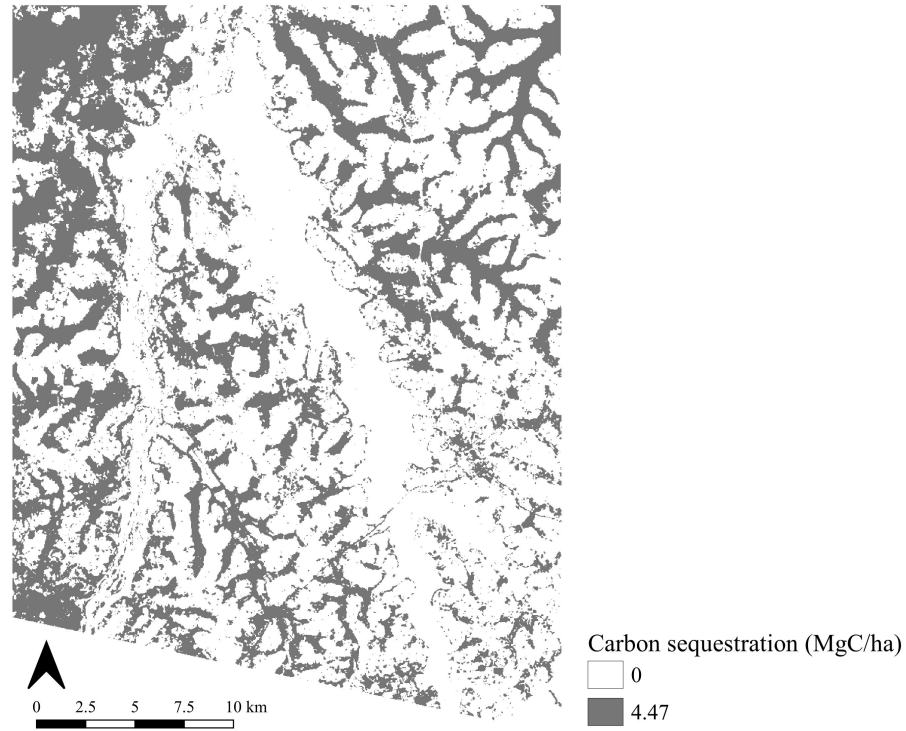


Figure 4.6: Map of the additional storage of carbon between the current and the future situations. Units are in MgC ha^{-1} .

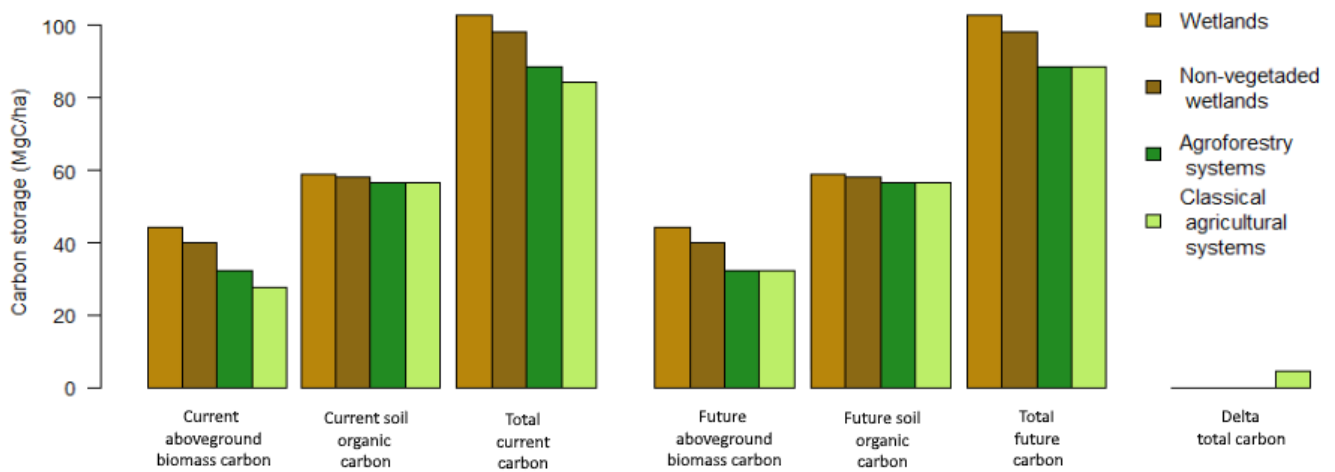


Figure 4.7: Summary plot of the stored carbon per class for the current and future situations. 'Delta total carbon' corresponds to the sequestered carbon between both situations.

Table 4.7: Carbon sequestration rates following the different scenarios. Units are in $\text{MgC ha}^{-1} \text{yr}^{-1}$.

Scenario	Years	Annual additional carbon storage
1	5 years	0.89
2	10 years	0.45
3	15 years	0.3
4	20 years	0.22

4.2.4 Economic valuation

Economic valuation returned by InVEST varied through the scenarios (due to discount rates): total economic valuation ranged from US\$ 203.55 ha^{-1} for the shortest time scenario (5 years) to US\$ 137.82 ha^{-1} for the longest time scenario (20 years) (Table 4.8). Initial outputs of the model were given in US\$ per pixel, but have been converted to US\$ ha^{-1} for better comparison. It represents the cost avoided by the storage of carbon through agroforestry systems. The total valuation column Table 4.8 considers the carbon stored over the entire study area. However, as mentioned in the methodology, valuation will instead be crossed with surface survey data of a sample of farms (section 4.3).

Table 4.8: Economic valuation (\$US) of the change from classical agricultural system to agroforestry system for the different scenarios.

Scenario	Years	Valuation		
		\$US ha^{-1}	\$US $\text{ha}^{-1} \text{yr}^{-1}$	\$US (total study area)
1	5 years	203.44	40.69	6 091 557.95
2	10 years	177.41	17.74	5 312 124.24
3	15 years	155.82	10.39	4 665 665.97
4	20 years	137.82	6.89	4 126 659.29

4.3 Valuation assessment per farm

4.3.1 Brief overview of the surveyed farms

Total area of the sample of the 205 surveyed farms varied between 0.17 and 24.71 ha, mean value being 2.82 ± 2.96 ha and 75% of the farms being under 3.4 ha (Fig. 4.8). Main land use was permanent cropland with a mean ratio of 0.67 ± 0.20 per farm, followed by arable land with a mean ratio of 0.27 ± 0.19 , permanent grassland with 0.03 ± 0.08 and woodland with 0.01 ± 0.04 ,

even though the latter two had more extreme values (Fig. 4.9).

The area under agroforestry practices also depended on the farms. The ratio (on the total area) varied between 0 and 1 which means that some farms did not have any surface under agroforestry practices, and some farms had their entire surface under agroforestry practices. 7.3% of the 205 farms had over 95% of their surface under agroforestry practices. This percentage rose to 9.7% for a percentage of at least 90%. 1.9% did not have any surface under agroforestry practices. Mean agroforestry ratio surface was 0.60 ± 0.24 (Fig. 4.10). There was no significant correlation between the total farm area and the ratio of the farm area under agroforestry practice: Spearman (because of the non-normality of the data) coefficient of -0.076 , p -value= 0.2783 .

Concerning the area of the farm dedicated to cocoa cultivation, ratios varied between 0.062 and 1, which means that all farms had at least part of their farm and some of them even their whole surface dedicated to cocoa cultivation. Mean proportion of the farm dedicated to cocoa was 0.53 ± 0.23 . 5.8% of the farms were entirely or at least at 95% (in terms of surface) dedicated to cocoa cultivation, and this percentage rose to 6.8% if we consider a dedication of at least 90%. The Spearman correlation coefficient returned a slight negative relation between the total farm area and share of cocoa cultivation of -0.325 (p -value= $1.998e - 06$), implying that larger farms tended to have a smaller proportion dedicated to cocoa (Fig. 4.11).

4.3.2 Economic valuation per farm

The economic valuation of potential additional carbon storage per unit of area (ha) (Table 4.8) was crossed with the area data of the sampled farms as shown in Equ.3.5. Some farms had an additional economic valuation of US\$ 0 . This is the case for the farms that already had their entire surface (or nearly) under agroforestry practices. Highest economic valuation values for scenarios 1, 2, 3, and 4, were US\$ 3518.99, US\$ 3068.7, US\$ 2695.27, and US\$ 2383.89 respectively. The sum values represent the total amounts that would have to be paid by a financier in a carbon-offset frame for all farms and the entire project, following the scenario taken into account (Table 4.9). Results have also been summarized following the size ranges of the farms (Table 4.10). These values correspond to the amount that could be allocated (by a willing stakeholder in the context of a carbon-offset market) to the farms if they switched their non-agroforestry surfaces to agroforestry practices. These values have then to be integrated in global reasoning, taking into account the price it would cost to technically make such change (and the management of it afterwards) and the potential loss of income by the transition to agroforestry systems (change in the agricultural yield for short-cycle crops and arable lands).

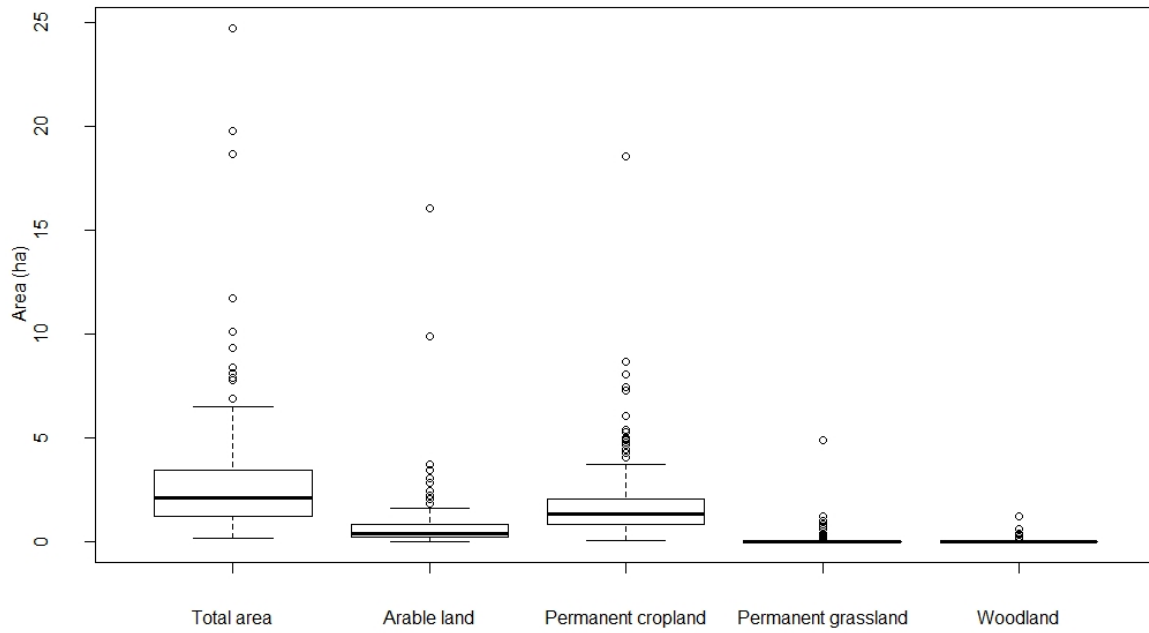


Figure 4.8: Boxplots of the total and land uses areas per farm, expressed in hectars (ha).

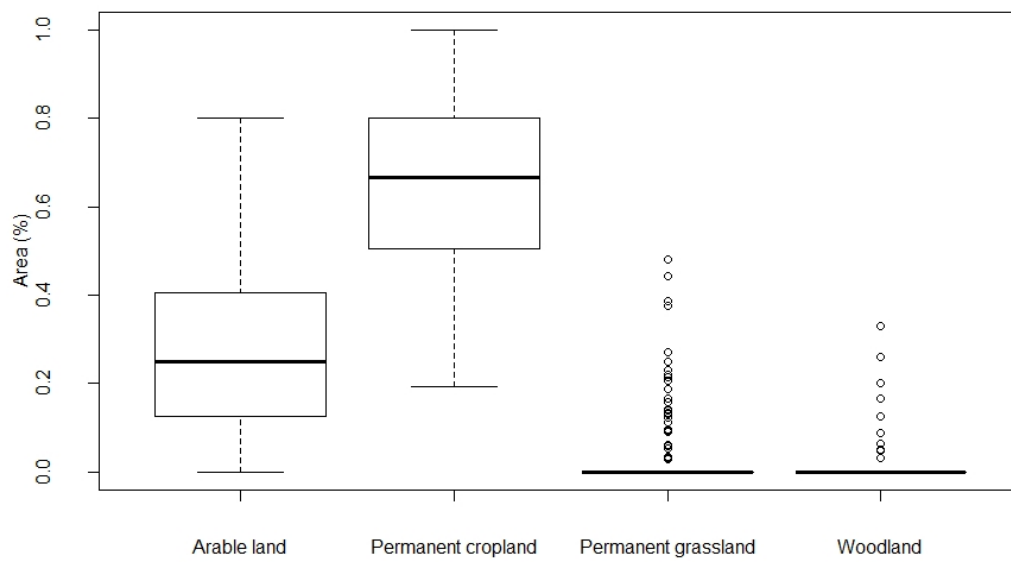


Figure 4.9: Boxplots of the land use ratios per farm (expressed in % of the total area).

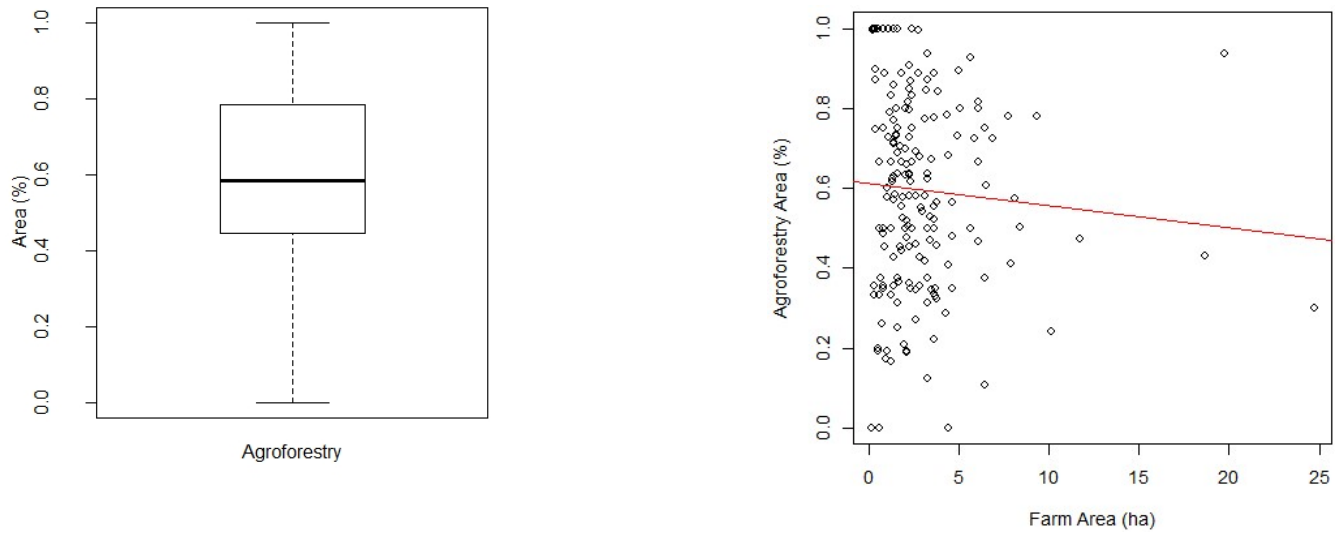


Figure 4.10: Boxplot of the ratio of the farm area under agroforestry (on the left) and correlation plot (+ trend line in red) with the farm area (on the right).

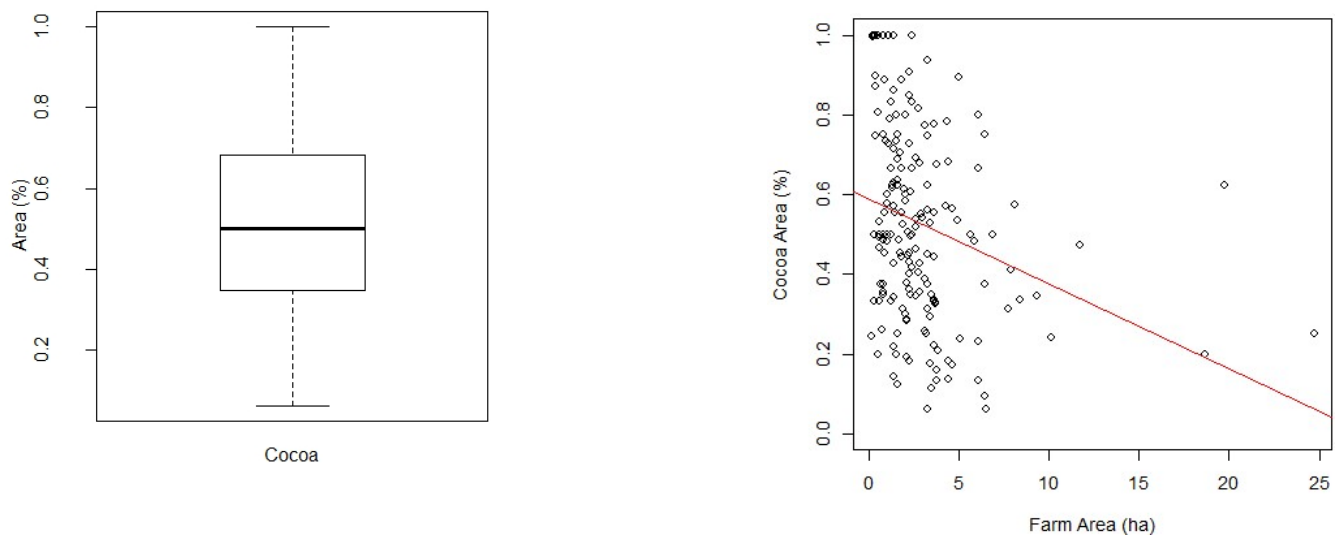


Figure 4.11: Boxplot of the ratio of the farm area dedicated to cocoa cultivation (on the left) and correlation plot (+ trend line in red) with the farm area (on the right).

4.3.3 Relation with cocoa production surface

Farms with greater share of land not currently under agroforestry practices could convert a larger proportion of land to agroforestry practice and thus potentially receive higher payments. Thus the quantification of the relation between the surface that is not currently under agroforestry practices and the proportion of the farm dedicated to cocoa is important as it shows if the payment will benefit major cocoa producers.

Among the sample of farms, 37% had 50% or more of their surface to be potentially converted of which 20% had at least half of their surface currently dedicated to cocoa cultivation. 8% of the 205 farms could potentially convert 75% or more of their land to agroforestry practices, of which only 19% had at least half of their surface dedicated to cocoa cultivation. In contrast, 40% of the farms had 33% or less of their surface that could be converted to agroforestry (because the rest already was) but among them, 75% already had at least half of their surface dedicated to cocoa cultivation.

Spearman correlation test (because of the non-normality of the variables) revealed a significant positive relation of 0.59 (p -value $< 2.2e-16$) between the agroforestry surface ratio and the cocoa surface ratio of the farms. Fig. 4.12 shows a clear positive linear relation, meaning that farms that did not have a large proportion of their surface under agroforestry practices yet, and thus that would eventually receive a payment for the change made, were not strongly dedicated to cocoa cultivation. For the observations that had almost perfect linear relation (in red), it is likely that it means that all cocoa cultures were under agroforestry practices. This concerns 56% of the farms of the sample. Removing the red observations, Spearman correlation test dropped to 0.15 and became non-significant (p -value = 0.1603). Separating the farms according to whether they already had their entire cocoa crop under agroforestry (as assumed from the statistics) (Group 1 = 56% of the farms) or not (Group 2 = 44%), a significant difference (t -test, p -value=0.013) between the averages of the proportions of potential area to convert became evident. The farms in Group 1 had on average 36% of their area to 'be' converted, and those in Group 2, 45%. This implies that even though farmers with already more environmentally friendly cocoa practices (agroforestry) would still receive a payment, farmers who could improve their cocoa practices would be candidates to receive more, relatively to their area.

Table 4.9: Main statistics of the economic valuation per farm. Units of the Total, Per year, and Per month are in US\$.

Scenario	Years	Statistic	Valuation		
			Total	Per year	Per month
1	5 years	Min	0.00	0.00	0.00
		Max	3 518.99	703.80	58.65
		1st quantile	82.33	16.47	1.37
		Median	125.14	25.03	2.09
		3rd quantile	312.85	62.57	5.21
		Mean	241.41	48.28	4.02
		Sum	49 488.85	9 897.77	824.81
2	10 years	Min	0.0	0.00	0.0000
		Max	3068.7	306.87	25.57
		1st quantile	71.8	7.18	0.6
		Median	109.1	10.91	0.91
		3rd quantile	272.8	27.28	2.27
		Mean	210.5	21.05	1.75
		Sum	43 156.48	4 315.65	359.64
3	15 years	Min	0.00	0.000	0.0000
		Max	2695.27	179.68	14.97
		1st quantile	63.06	4.20	0.35
		Median	95.85	6.39	0.53
		3rd quantile	239.62	15.97	1.33
		Mean	184.90	12.33	1.03
		Sum	37 904.63	2 526.97	210.58
4	20 years	Min	0.000	0.0000	0.00000
		Max	2 383.89	119.19	9.93
		1st quantile	55.77	2.79	0.23
		Median	84.77	4.24	0.35
		3rd quantile	211.94	10.60	0.88
		Mean	163.54	8.18	0.68
		Sum	33 525.47	1 676.27	139.69

Table 4.10: Table of the mean valuation per farm based on the area statistics of the surveyed farms. Units of the Total, Per year, and Per month are in US\$.

Scenario	Years	Farm area quantile		Valuation		
				Total	Per year	Per month
1	5 years	min to 1st	0.17 to 1.21 ha	66.68	13.34	1.11
		1st to median	1.21 to 2.12 ha	127.74	25.55	2.13
		median 3rd	2.12 to 3.44 ha	207.41	41.48	3.46
		3rd to max	3.44 to 24.71 ha	562.31	112.46	9.37
2	10 years	min to 1st	0.17 to 1.21 ha	58.15	5.814	0.48
		1st to median	1.21 to 2.12 ha	111.4	11.14	0.93
		median 3rd	2.12 to 3.44 ha	180.87	18.09	1.51
		3rd to max	3.44 to 24.71 ha	490.36	49.04	4.09
3	15 years	min to 1st	0.17 to 1.21 ha	51.07	3.40	0.28
		1st to median	1.21 to 2.12 ha	97.84	6.52	0.54
		median 3rd	2.12 to 3.44 ha	158.86	10.59	0.88
		3rd to max	3.44 to 24.71 ha	430.68	28.71	2.39
4	20 years	min to 1st	0.17 to 1.21 ha	45.17	2.26	0.19
		1st to median	1.21 to 2.12 ha	86.53	4.33	0.36
		median 3rd	2.12 to 3.44 ha	140.50	7.02	0.59
		3rd to max	3.44 to 24.71 ha	380.93	19.05	1.59

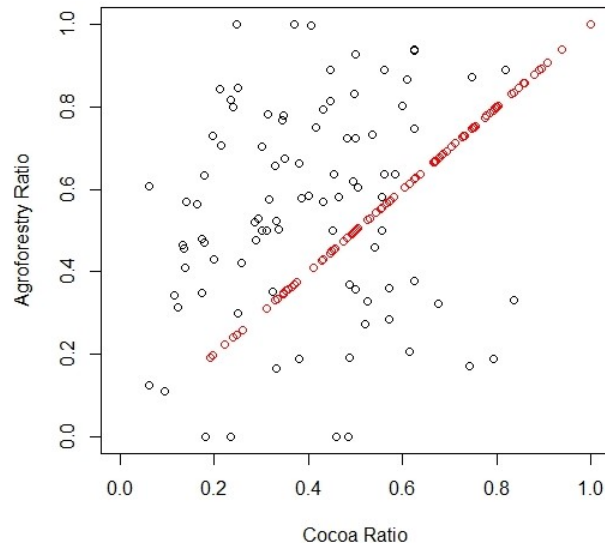


Figure 4.12: Relation between the agroforestry surface ratio and the cocoa surface ratio of the farms. Red observations concern the values for which the difference in absolute values between the ratios of the two variables is ≤ 0.01 .

Chapter 5

Discussion

5.1 Classification map

The obtained classification map showed relatively good Kappa Coefficient. The agroforestry system and the classical agricultural system classes seemed to match the geomorphological features of the area. Without taking into account (non-vegetated) wetlands, classical agricultural systems seem to correspond to "lighter green" areas, and agroforestry systems to "darker green" areas on the Landsat-8 satellite image (Fig. 3.1); "lighter and darker green" areas appearing to have geomorphological structures marked by water processes. This suggests that the presence of agroforestry systems or classical agricultural systems is strongly influenced by the structure of the geomorphological features of the area due to limiting environmental factors. An hypothesis of the limiting factor was the soil water content: agriculture systems could have been implemented on more humid lands to limit the need of irrigation, and perennial crops in agroforestry on drier lands (as they can handle longer dry spells better). The identified classical agricultural system lands coincides roughly with the seasonal wetlands identified by the World Resources Institute (WRI) in an article about linking wetlands and sanitation ([WRI, 2009](#)) (see Appendix, Fig. 2). However, a wetness index showed the opposite trend (see Appendix, Fig. 3), doubt hence remains. On another note, what would be the rational for wanting to convert the current agricultural systems to higher agroforestry cover? Would an increase of agroforestry cover be possible from both an environmental as well as farming household's with food crop requirements point of view? Even though food crops growing in different strata of the agroforestry systems could be increased (like plantain, fruit trees, taro cassava,...), they also have to keep food crops like beans and maize. Thus, the two types of production should coexist anyway. Furthermore, Mukono being a peri-urban district of Kampala is subject to inward migration flows. Therefore, [Ekesa et al. \(2015\)](#) stated that the

district should focus on intensive crop-livestock production systems because of the high pressure on land. This would go against the purpose of this study, although it does not necessarily apply precisely to our study area.

5.2 Carbon storage assessment

5.2.1 Comparison with literature

Current carbon stock

Given the methodology, current carbon stock estimations per class have been assessed based on literature layers (Harris et al., 2021; Sanderman et al., 2018). Taking into account only two of the major carbon pools, it gave a carbon stock value estimation of 88.63 MgC ha⁻¹ for the agroforestry lands (32.13 MgC ha⁻¹ of aboveground biomass carbon stock and 56.49 MgC ha⁻¹ of soil carbon stock). In comparison with agroforestry carbon stock estimations of other authors (see Appendix, Table 1), my estimation was either within the value ranges or below. However, it is the case for the four classes of the LULC classification map, and not only for the agroforestry class, which lowers the relevance of such comparison. Indeed, the variation between the estimated carbon stocks of the different classes is lower than expected. This could either be due to the simplified classification of the land use area leading to less differentiated respective carbon values, to the not fine enough spatial scale of the classification, or to a little spatial variation of carbon stock in the study area *per se*.

Note that in any case, it is hard to compare the obtained value of the agroforestry class to other authors because values vary highly between different studies. Indeed large variabilities exist when assessing the carbon stocks of complex agroforestry systems (understand here shaded perennial crops like coffee or cocoa mixed with other trees) (Albrecht and Kandji, 2003). It is necessary to pay high attention to what pool(s) is(are) being measured and to the units, and to mention them clearly, as confusion between the values, misinterpretation, and inconsistency can occur. Nair et al. (2010) underlines that procedures should be more rigorous and consistent when assessing agroforestry carbon sequestration because current methodologies and related assumptions vary widely. Consequently, even though a comparison with carbon stock values from other authors is interesting, it will not be considered as a reference indicator of a good estimation. Nevertheless, distribution of the carbon stock shown by the results among the aboveground biomass (36%) and the soil (64%) corresponds to the approximations mentioned by Nair et al. (2010), i.e. 30% and 60% respectively (remaining 10% are due to the neglected pools).

Additional storage of carbon

The results have shown that a conversion of all the classical agricultural lands to agroforestry systems could increase the carbon stock of 4.47 MgC ha^{-1} for the converted lands. Knowing that the current stock of the classical agricultural lands has been estimated to 84.15 MgC^{-1} , it means that it would increase of 5.3% per unit area. This is significantly lower than the IPCC's meta-analyses, showing that agroforestry store 20-33% more soil carbon than conventional agriculture (IPCC, 2022a). Comparison with literature must be taken carefully, specially when considering sequestration rates. Indeed, the carbon value given in output by the model is the amount of carbon that could be additionally stored due to a certain change. But it does not take into account the amount of continuous sequestration into the systems, even if there was no change or after the change. Yet, the additional carbon amount can be converted to annual rates ($\text{MgC ha}^{-1} \text{ yr}^{-1}$) considering a certain period of time for the implementation (in our case the 4 different time scenarios), like it has also been done for instance by Dargains and Cabral (2021).

5.2.2 Environmental impacts

Among the 205 farms, a total area of 243.26 ha could be potentially converted to agroforestry. In addition to the mitigation effect that agroforestry systems have on global climate change (by capturing atmospheric carbon) and on the enhancement of the local climate conditions (Humphrey et al., 2017), it also has other environmental impacts.

The benefits to the soil from converting to agroforestry may not be as valuable as imagined. The sampled farms did not seem to have large soil degradation problems. Only 4% of the sample reported having signs of severe soil compaction due to livestock or machinery (average of the proportion of agricultural area affected being 7.9%). And also 4% (different than the 4% previous farms, except for one) reported having agricultural area that has been degraded over the last 20 years or that can no longer be used for farming (average of the proportion of agricultural area affected being 9.7%). The low proportion of compaction problem could be explained by the low livestock density and rare use of machinery. However, this is in contradiction with Ekesa et al. (2015) who reported that there was a decline in Ugandan soil fertility (as a result of soil nutrient depletion due to over-cultivation and soil mining) and an increase of soil erosion problems (mainly due to wind during dry seasons, along with population pressure, poor methods of farming, over-grazing and vulnerable soils). And at a district level, Masaka and Mukono seemed to have most depleted soils among several close-located to Kampala districts (Ekesa et al., 2015).

The biological benefits could be of major interest for the farms, notably with regard to the pollination issue. 70% of the sample reported using active substances which are considered toxic to bees

(with strongest toxicity of the substances used being in average rated to 3 on a 1-5 rating scale). Whether a conversion to agroforestry may alleviate pressure on forests of the surrounding areas have not been explored.

Water quality and hydrological cycles improvement can always benefit to farmers. Even if 57% of the sample have declared taking steps to adapt to the consequences of climate change, non of them is insured against natural hazards (including droughts and flooding). Existing agroforestry systems of the sample of farms consist in average in 3 layers (range going from 2 to 6 layers). However, comparison at first sight with the fact that intermediate levels of canopy shade (40 to 60%) could protect cocoa trees from drought ([Middendorp et al., 2018](#)) is difficult because of different measurements.

5.3 Economic valuation assessment

5.3.1 Different time scale scenarios

Variation of the economic valuation

Although the assessment of the potential additional carbon storage was constant for the four time scenarios, economic valuations did vary among them. For a sequestration of 4.47 MgC ha^{-1} (due to a conversion to agroforestry systems), results have shown that farmers could receive US\$ 137.82 ha^{-1} if the conversion to agroforestry is done in 20 years, and US\$ 203.44 ha^{-1} if it is done in 5 years, which is about 1.5 times more. This means that the price ranges from US\$ 30.83 to US\$ 45.51 MgC^{-1} . Price decreases through time because of the annual market discount on the price of carbon and the annual rate of change in price of carbon. First the market discount rates, even if set lower than in other studies (e.g. 6% by [Dargains and Cabral \(2021\)](#)), still reduces the value of carbon sequestration over time because of the preference of society for immediate benefits. Carbon that can be stored immediately (or understand, soon) is preferred to carbon that could be stored in the future. Therefore, short time scenarios have higher economic valuation. Note that these are theoretical values, which do not take into account the practical constraints (biological, social, ...) of the implementation. In the same way, the annual rate of change in price of carbon, set positively, also reduces the economic value of carbon sequestration over time. The non-linear response of the climatic system to atmospheric carbon concentrations implies that mitigation measures must be undertaken at short timescale. Even if the meaning of threshold values as points of no return is still being discussed, it reflects anyway the fact that the more we wait, the more impacts will be harder to mitigate. This is why, in 15 years time scale (difference between scenario 1 and 4), price

for carbon sequestration drops of US\$ 65.62 ha⁻¹ (or US\$ 14.67 MgC⁻¹) for conversion of lands to agroforestry.

Note that the referred SCC (US\$ 51), on the one hand was only one of the values recovered in literature, and, on the other hand, is very likely to change through time due to the context of current events (on a much smaller time scale than that of the scenarios). Therefore it might not be up to date in the scenario time component.

Scenarios differentiation

In addition, even if short time scale scenarios return higher economic valuation because of their faster implementations and thus effectiveness, it does not take into account the way such implementations are reached and their eventual associated externalities. For the 5 years time scale scenario, we can imagine that a company could arrive with pre-grown trees and plant them simultaneously and rapidly. This would lead to a faster implementation of agroforestry systems. Assuming this project could practically completely take place in 5 years, carbon would be sequestered earlier and farmers would begin to perceive earlier the associated co-benefits production (fruits, timber, firewood,...). Whereas having to wait 20 years for it might be a discouraging factor ([Ekesa et al., 2015](#)). However, such fast project might go along with greater biological and environmental disturbances. In contrast, planting seeds or seedlings, either by the farmers themselves or a company, might be more of a soft eco-friendly planting type, better adapted to the environment. But waiting time for good production benefits might be longer. Since I found little literature on the subjects, it all remains however in the state of hypotheses.

In addition, even if short and longer time scale scenarios can be given hypothetically in the model, the sequestration of the amount of carbon storage assessed might not follow biologically in practice due to the different growth cycles of the plant necessary for carbon sequestration. [Nair et al. \(2009\)](#) underlies that due to growth physiology, long periods of time are required to realize the potential for additional carbon sequestration in soils. The IPCC recommends at least a 20 year period for soil carbon sequestration accounting ([Feliciano et al., 2018](#)). Therefore, 5 years time period might not be realistic nor adequate. Note that, no matter what scenario is considered, the systems has limited potential in carbon sequestration, unless they are continuously significantly modified by management interventions (like new tree planting or fertilization practices) ([Nair et al., 2009](#)). The type of tree and their development cycle time are also determining for the feasibility of the scenarios. Fast-growing species may accumulate more carbon than slow-growing species on short term, but the trend is reversed when considering long term ([Nair et al., 2010](#)). In addition, whether

native tree species are superior and/or better adapted to exotic ones, is still uncertain (Nair et al., 2010). However, Vaast and Somarriba (2014) stated that agroforests trees shouldn't be limited to native species, and that functional diversity would be enhanced by mixing them with local or exotic trees to target more specific functions. In Mukono, according to Ekesa et al. (2015), agroforest tree crops such as ficus (*Ficus natalensis*), musambya (*Markhamia lutea*), jack fruit (*Artocarpus heterophyllus*), or pawpaw (*Carica papaya*), are frequently used.

5.3.2 Socioeconomic impacts

When addressing sustainability, research is frequently limited to one dimension, social and governance-related sustainability often receiving less attention than environmental and economic dimension. A larger point of view integrating other sustainability dimensions and their interrelations is needed to fully tackle cocoa production systems sustainability (Tennhardt et al., 2022).

An income diversification could be of high value to the smallholders, as only 32% of the sample reported having other sources of income (related to agriculture and which contribute more than 10% of their income) besides farming. For them, the range of other sources of income varies from 1 to 4, with a median of 1. Thus, it could be a great opportunity to increase the income diversification of the farms, at least for the remaining 78% having no other source of income. Following Ekesa et al. (2015), there is also opportunities due to available high yielding varieties of fruit trees and given that there is reasonable local market in Mukono for fruit (and other tree products) that could be enhanced by value addition. And agroforestry can lead to a more diverse diet and improvement of the nutritional status of Mukono's populations. Also, such agroprocessing ventures could contribute to creating employment for youth (Ekesa et al., 2015).

However, Tennhardt et al. (2022), from whom the socioeconomic database used comes and who works (in part) on the same sample of farms, underlines that despite some important social and economic co-benefits, there are also several social and economic trade-offs when implementing environmentally-friendly production practices. As previously briefly mentioned in section 5.1, it is important to keep in mind that optimum configuration of agroforestry systems (for maximum carbon sequestration, like the extreme conversion scenario of this study) is unlikely to occur totally, because communities strongly depend on other systems providing products and services. Farmers operate under diverse socioeconomic, institutional, and ecological contexts. A systemic and co-ordinated approach is needed, taking into account several types of ecosystem services, as well as development goals and the interrelationships associated (Feliciano et al., 2018).

Figure 5.1: Production Operating Cost Estimate - *Eucalyptus*. Concerning the assessment of land use/cover changes and carbon dynamics at farm level in a Brazilian area. "Scenario 3" refers to forest plantation and "Scenario 4" refers to silvopastoral system implementation. Source: [Dargains and Cabral \(2021\)](#).

Item	Scenario 3 (US\$/ha)	Scenario 4 (US\$/ha)
Planting	533.07	355.22
Land annual cost*	62.72	62.72
Maintenance (first year)	128.99	128.99
Maintenance (annual cost)	45.55	40.11
Total for 10 years	1744.76	1512.51

5.3.3 Integration of the economic valuation in the frame of an offset carbon market

Comparison with average wage

According to the [Global Living Wage Coalition \(2021\)](#), average living wage for the Lake Victoria Basin in rural Uganda is US\$ 203 per month. The results have shown that farms willing to enter an offset carbon market could be paid US\$ 4.02, US\$ 1.75, US\$ 1.03 and US\$ 0.68 in average per month for implementation time scale scenarios of 5, 10, 15, and 20 years respectively. The maximum amounts received by some farmers could be US\$ 58.65, US\$ 25.57, US\$ 14.97 and US\$ 9.93 per month respectively. Thus, average and maximum additional income share could be of 2% and 29%, 0.9% and 13%, 0.5% and 7%, and 0.3% and 5%, respectively for the four scenarios and taking as reference the average living wage for the Lake Victoria Basin. These low potential payment amounts, especially when considering the average values, could be explained by the fact that in most cases carbon pools are limited in their capacity and carbon accumulation rates are relatively low in most agroforestry systems, restricting potential carbon payments ([Luedeling et al., 2011](#)). Moreover, this income-augmenting effect is to integrate in a broaden vision taking into account several costs related to this adoption.

Associated costs

Implementation

In their study, [Dargains and Cabral \(2021\)](#), in addition to assessing the economic valuation of carbon storage through InVEST for a Brazilian region, also estimated the production operating cost per ha: planting, land annual cost, maintenance of the first year, and maintenance (annual cost) after the first year (Fig. 5.1). [Dixon et al. \(1994\)](#) gathered estimations of investment costs

per ha for small farm fuelwood and agroforestry systems in Ghana, Malawi, Nigeria and Senegal: US\$ 20, US\$ 35, US\$ 45 and US\$ 30 ha⁻¹ for each country respectively (estimation of 1994). This would equal to US\$ 39.02, US\$ 68.28, US\$ 87.79 and US\$ 58.52 ha⁻¹ nowadays (by converting 1994 to 2022 US\$). Similarly, [Henry et al. \(2009\)](#) recalled the estimation of carbon sequestration costs per MgC made by [Woomer et al. \(1998\)](#) for smallholder farms of East African highlands: US\$ 47 MgC⁻¹ (estimation of 1997), which would equal to US\$ 83.77 MgC⁻¹ nowadays (by converting 1997 to 2022 US\$). In another order of magnitude, the IPCC ranks agroforestry in the high costs of implementing adaptation options, considering its implementation costs to be over US\$ 5000 ha⁻¹ ([IPCC, 2022b](#)). Obviously these assessments are difficult to compare directly, even among themselves, notably because of the different methodologies and units, case studies, and countries (thus implying different costs, tree species, etc.), but it provides examples of similar approaches.

Certification

If farmers are willing to convert to organic production, they will also have to pay for the associated certification costs to be recognized as such. Along with foreign certification bodies operating in the country, since 2004 Uganda accounts for its own internationally accredited local certification body: The Uganda Organic Certification Limited (Ugo Cert). Most of farm smallholders in Africa are ‘organic by default’, and wouldn’t have to make major changes theoretically in their processes to get the certification (without taking into account the administrative side). Yet, due to the low economic level, certification costs typically have to be met by the buyer ([Jones and Gibbon, 2011](#)); certification costs are still very high for most smallholders ([GIZ, 2021](#)). Group certification systems could reduce certification costs by an estimated ten times ([Preissel and Reckling, 2010](#)). Improving PES, extent of carbon markets, rise of carbon prices, and certification schemes are key elements to incentivize and reward smallholders for the environmental benefits their shaded agroforestry systems provide ([Middendorp et al., 2018](#)).

Income potential loss

Finally, another component of the financial budget is the potential farmers’ income loss due to reduction of cocoa yield (in comparison with full-sun and high inputs monocultures). But it is difficult to assess quantitatively given the data at disposal.

Integration

The associated costs (even if averaging and smoothing out the trends and values due to the high possibility of non full comparability of the studies) can be considered as greatly exceeding the esti-

mations of potential financial compensations through carbon markets (US\$ 137.82 to US\$ 203.44 ha⁻¹ / US\$ 30.83 to US\$ 45.51 MgC⁻¹, following the time scenario). 33% of the surveyed farms reported that the income generated during the five last years did not cover their costs at all. Therefore, taking on the total finance of the implementation may be complicated - if not impossible - for a large proportion of smallholders. This goes along with [Luedeling et al. \(2011\)](#) stating that the poorest households are likely to benefit least from carbon sales because of the initial investments required by the implementation. To benefit from carbon sequestration as a mean to reduce poverty, focus should rather be pro-poor oriented than based on purely market-based approach ([Luedeling et al., 2011](#)). A big knowledge gap among the studies focusing on carbon sequestration is "the lack of efforts to estimate the transaction costs for implementing carbon projects, as well as the costs of measurement, reporting and verification of the sequestered carbon" ([Luedeling et al., 2011](#)). Agroforestry systems deliver many other added benefits, like yield increases and additional marketable products. Therefore, economic analysis should focus on carbon credits in whole farm budgets (see Appendix, Fig. 4) ([Luedeling et al., 2011](#)).

The amount received by the farms for the sequestration compensation would be paid by an entity or company wishing to compensate for their emissions. The costs related to the implementation and maintenance could either be paid by the same latter entity or company, by the chocolate company Schöki, or by a public fund. Suggesting the smallholders as funder would be a non-incentive for the project to proceed. Complete and thorough economic budgets for each farm could be considered for future research in order to see if at least compensation and at best benefit can be reached.

5.4 Practical implementation constraints

To achieve any 'carbon sequestration through reforestation' type of project, there are different components of potentials (biophysical, technical, economic, and practical potentials), but also constraints that go along with them (see Appendix, Fig. 5). Many studies, when assessing the carbon sequestration potential of agroforestry, miss one or more components ([Luedeling et al., 2011](#)) and therefore deviate one step away from reality. This implies that in most situations the practical carbon sequestration is lower than the economic calculations ([Luedeling et al., 2011](#)). A typical dimension that is not taken into account in the valuation results of this study, is the willingness of farmers to take part in it. Whether farmers accept to try new land management options might depend on the economic outcome but also on a variety of other factors. And even after a trial, it is not said that they will adopt those management options. Indeed, pests, drought,

bush fires, damage by livestock, and other biotic and abiotic factors can affect the performance of trees in the initial trials (Luedeling et al., 2011). Other factors that may influence adoption include land tenure, cultural norms, and household power structures of many regions. Other factors that may influence carbon sequestration potential include lack of management options information and adequate input. Also, farmers may be reluctant to plant trees with long gestation periods, and problems between neighbours may arise if trees are planted along farm boundaries (Ekesa et al., 2015).

Thus, interventions should be thought in a comprehensive way (Tennhardt et al., 2022). Even if socio-psychological factors play indirect (or hidden) roles in agroforestry management, it has key consequences on the management decisions taken and thus the sequestration (Luedeling et al., 2011). Finally, Roshetko et al. (2007) underlines that, in order to implement, for example, a CDM¹ project, the following elements must be present beforehand: "areas of underutilized, low-biomass landuse systems that are available for rehabilitation; smallholders interested in tree farming; accessible markets for tree products; a supportive local government and sufficient infrastructure; and a transparent and equitable relationship between project partners".

We can see that a conversion of all classical agricultural systems to agroforestry systems is probably not adoptable because not realistic and most likely not profitable for the farmers in current context. A solution could be the conversion of a limited share and to set aside a proportion of monoculture, as suggested by Middendorp et al. (2018). This way, farmers could continue to benefit from a sufficient income and products and services associated, while also having increasing agroforestry benefits. Some beneficial impacts on the environment would still occur (like greater forest connectivity (Middendorp et al., 2018), and carbon stock would increase, if we are willing to accept that it will occur at smaller scale. One last point to acknowledge, is whether funding would also be established if the farm already has all of its cocoa production under agroforestry, but not necessarily the rest of its area. This situation clarification is important as it could concern about 56% of the sample of cocoa farmers, who in average still have 36% of their surface (other than cocoa) which are not under agroforestry practices.

¹Clean Development Mechanism comes from the Kyoto Protocol (Article 12), and has as objectives both reducing greenhouse gas emissions and contributing to sustainable development (Roshetko et al., 2007).

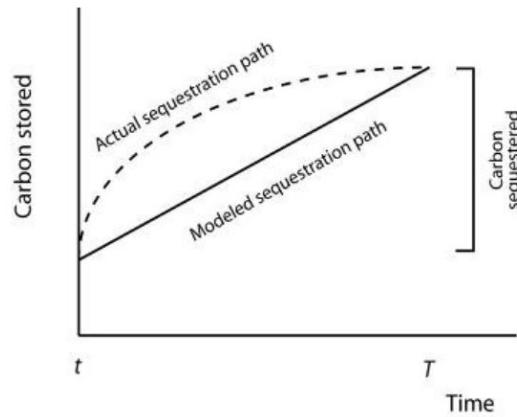


Figure 5.2: Model linear carbon sequestration path vs. actual nonlinear carbon sequestration path.
Source: [Natural Capital Project](#) (sd)

5.5 Methodological reflection

InVEST Carbon Storage and Sequestration model's limitations

First, the model considers that none of the LULC classes gains or loses carbon over time. It assumes an average fixed storage level for each class (on basis of the carbon pools), and only takes into account the additional carbon that is stored or released due to a LULC conversion, when pixel values change. This means that if a pixel value does not change, the model will consider a sequestration value of 0. Thus, it neglects natural succession. An alternative to this limitation could have been to differentiate, within the classes, sub-classes based on the age (for example tree age for forest, and plantation age for perennial crops), and to elaborate time scenarios based on age-differentiated maps ([Natural Capital Project](#), sd). Secondly, the model does not take into account variations within the LULC classes. It takes the average values of the carbon pools for each class. Depending on how large are the surface areas of the classes, temperatures, elevation, and climate bands could influence carbon storage values within a same class. An alternative solution would be to refine the classification by making sub-classes taking into account those variations. But it requires a certain detail level of the data ([Natural Capital Project](#), sd). Finally, InVEST considers a linear carbon sequestration, which clearly deviates from reality, as actual carbon sequestration follows a nonlinear path ([Nair et al., 2010](#)) until a level of equilibrium is reached (Fig. 5.2).

Input's limitations

The LULC shows a clear spatial pattern between the classical agricultural systems and agroforestry systems. In addition to a geomorphological induced hypothesis, it might also suggest that classes

separation was reflecting another differentiation than the agroforestry systems/classical agricultural systems one, and that they have been incorrectly established and interpreted. It is also important to acknowledge that all farms location from the sample fall into the agroforestry system class. This does not necessarily mean that they are all fully dedicated to agroforestry, as the database confirms. This resolution scale problem is one of the limitation I encountered during the conception of the LULC map with a Landsat-8 imagery. Land-use at farm-scale was not observable and differentiable on the imagery. Another reason could eventually be that location data was given in single points. Exact polygons of the areas of the farms might have included classical agricultural system areas. Moreover, the component of agroforestry tree species has not been taken into account in the analysis, whereas it affects largely carbon storage and sequestration processes (Humphrey et al., 2017). For example, instead of increasing the agroforestry cover, I could have considered improving existing agroforests, including through the species of trees considered. To get closer to the reality of the field, classes and their conversion could have been elaborated with the help of a local stakeholder (e.g. smallholder), like in Dargains and Cabral (2021). Even if it would have been a little beyond the scope of this study.

Concerning the carbon pools, due to the fact that the belowground and dead organic matter were set to zero, it has increased the degree of simplification and the deviation from reality. Missing carbon pools could have either been found in literature, or assessed by assuming a linear relation with other pools, like Dargains and Cabral (2021) assuming dead organic matter carbon content to be 10% of the aboveground biomass carbon content. Also, the aboveground biomass carbon values coming from Harris et al. (2021) refer to year 2000. In twenty years time, changes have probably taken place. With regard to the soil organic content, the data used (Sanderman et al., 2018) only takes into account the first 30 cm of the soil, and neglects deeper layers.

Being aware of these limitations, it is important to keep in mind that this study is an hypothetical extreme case to detect major trends, and does not pretend to consider each farm's specifications.

To go further

Methodological focus could have also been turned towards other types of ecosystem services which, to my knowledge, have been less addressed in literature than carbon storage and sequestration assessments. Other beneficial ecosystem services are often mentioned, but rarely quantified. In addition Luedeling et al. (2011) noted that environmental trade-offs between the retention of trees for carbon sequestration or using them as fuel, fodder, and fertilizer, have not yet been explored sufficiently. This point could also be further explored.

Chapter 6

Conclusion

Converting farming lands to agroforestry systems is a way to sequester additional atmospheric carbon, and thus to contribute to climate change mitigation. Cocoa production, which has a high global demand and is becoming increasingly important in Uganda, can typically take place in agroforestry schemes. If cocoa farmers adopted more sustainable production practices and consequently stored more carbon in their land, they could receive compensation for the increased provision of this ecosystem service through carbon markets.

This study aimed at assessing the potential economic benefit of 205 Ugandan smallholder cocoa farmers in conversion to organic certification through participation in a carbon-offsetting scheme. Results from the InVEST model showed that conversion of short-cycle crop land to shaded agroforestry systems could result in an increase of 5.3% per unit area of the actual carbon stock; although not easily comparable with other values in the literature. Further economic valuation pointed to an associated positive financial compensation for such storage; higher compensations corresponding to faster implementations, and vice versa. Farmers could receive US\$ 137.82 ha⁻¹ if the conversion to agroforestry is done in 20 years, and 1.5 times more if done in 5 years. Carbon storage benefits on a global scale, decreasing global warming, but also on a local scale to farmers, bringing several environmental and socioeconomic co-benefits. Nevertheless, additional funding must be considered to address the associated costs (e.g. implementation, maintenance and certification) without loss of income to the farms.

However, converting all of the farms' remaining land to agroforestry systems seems neither rational nor possible, taking into account the farmers' needs of staple food production. Furthermore, the short theoretical time scenarios may not be realistic or feasible in practice. Therefore, biological, environmental, social, and economic constraints of the field reality should be incorporated into further more detailed analysis. This study, far from pretending to propose a specific plan of carbon offsets implementation, offers a general approach to assess the potential for a certain sample of farms.

Bibliography

- Albrecht, A. and S. T. Kandji (2003, October). Carbon sequestration in tropical agroforestry systems. *Agriculture, Ecosystems & Environment* 99(1), 15–27.
- Buckley Biggs, N., J. Hafner, F. Mashiri, L. Huntsinger, and E. Lambin (2021, February). Payments for ecosystem services within the hybrid governance model: evaluating policy alignment and complementarity on California rangelands. *Ecology and Society* 26(1). Publisher: The Resilience Alliance.
- Claus, G., W. Vanhove, P. V. Damme, and G. Smagghe (2018, June). Challenges in Cocoa Pollination: The Case of Côte d’Ivoire. In P. W. Mkwala (Ed.), *Pollination in Plants*. InTech.
- Danley, B. and C. Widmark (2016, June). Evaluating conceptual definitions of ecosystem services and their implications. *Ecological Economics* 126, 132–138.
- Dargains, A. and P. Cabral (2021, December). A GIS-based methodology for sustainable farming planning: Assessment of land use/cover changes and carbon dynamics at farm level. *Land Use Policy* 111, 105788.
- Dixon, R. K., J. K. Winjum, K. J. Andrasko, J. J. Lee, and P. E. Schroeder (1994, May). Integrated land-use systems: Assessment of promising agroforest and alternative land-use practices to enhance carbon conservation and sequestration. *Climatic Change* 27(1), 71–92.
- Ekesa, B., J. Rao, J.-J. Cadilhon, P. Ayebare, B. Bashaasha, C. Muyanja, M. Tenywa, D. Tumusi, J. Twinamasiko, J. Jagwe, N. Mango, and P. Muchunguzi (2015, December). *A situational analysis of agricultural production and marketing, and natural resource management systems in the central region of Uganda*.
- FAO (2014). *Country profile – Uganda: AQUASTAT Report*. FAO AQUASTAT Report. Rome, Italy: FAO.
- FAO (2015a). Agroforestry. <https://www.fao.org/forestry/agroforestry/80338/en/>. Last visited 2022-05-06.
- FAO (2015b). Country fact sheet on food and agriculture policy trends - Uganda. Policy brief, Food and Agriculture Organization of the United Nations.

- FAO (2022). Ecosystem Services & Biodiversity (ESB). <http://www.fao.org/ecosystem-services-biodiversity/background/en/>. Last visited 2022-06-02.
- FAO and ICRAF (2019). *Agroforestry and tenure*. Number 8 in Forestry Working Paper. Rome, Italy: FAO.
- FAOSTAT (2022). Crops and livestock products. <https://www.fao.org/faostat/en/#data/QCL/visualize>. Last visited 2022-04-05.
- Feliciano, D., A. Ledo, J. Hillier, and D. R. Nayak (2018, February). Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? *Agriculture, Ecosystems & Environment* 254, 117–129.
- FiBL (2021). The State of Sustainable Markets 2021. <https://vss.fibl.org/vss-report/report-2021>. Last visited 2022-06-06.
- FiBL (2022). Enhancing supply chain stability, resilience and sustainability through improved sub-supplier management – chocolate and cotton apparel case studies. <https://www.fibl.org/en/themes/projectdatabase/projectitem/project/1478>. Last visited 2022-06-07.
- GIZ (2021). Sector Brief Uganda: Organic Agriculture. *Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH*, 8.
- Global Living Wage Coalition (2021). Living Wage for Rural Uganda. <https://www.globallivingwage.org/living-wage-benchmarks/living-wage-for-lake-victoria-basin-uganda/>. Last visited 2022-06-05.
- Gopaulchan, D., L. A. Motilal, F. L. Bekele, S. Clause, J. O. Ariko, H. P. Ejang, and P. Umaharan (2019, March). Morphological and genetic diversity of cacao (*Theobroma cacao* L.) in Uganda. *Physiology and Molecular Biology of Plants* 25(2), 361–375.
- Gómez-Baggethun, E., R. de Groot, P. L. Lomas, and C. Montes (2010, April). The history of ecosystem services in economic theory and practice: From early notions to markets and payment schemes. *Ecological Economics* 69(6), 1209–1218.
- Harris, N. L., D. A. Gibbs, A. Baccini, R. A. Birdsey, S. de Bruin, M. Farina, L. Fatoyinbo, M. C. Hansen, M. Herold, R. A. Houghton, P. V. Potapov, D. R. Suarez, R. M. Roman-Cuesta, S. S. Saatchi, C. M. Slay, S. A. Turubanova, and A. Tyukavina (2021, March). Global maps of twenty-first century forest carbon fluxes. *Nature Climate Change* 11(3), 234–240. Number: 3 Publisher: Nature Publishing Group. [Accessed on 2021-11-24 from Global Forest Watch].
- Henry, M., P. Titttonell, R. Manlay, M. Bernoux, A. Alain, and B. Vanlauwe (2009, January). Biodiversity, carbon stocks and sequestration potential in aboveground biomass in smallholder farming systems of western Kenya. *Agriculture, Ecosystems & Environment* 129, 238–252.
- Humphrey, A., R. Onwonga, S. Kuyah, and M. Tsingalia (2017, January). Carbon stocks and stock changes in agroforestry practices: A review. *Tropical and Subtropical Agroecosystems* 20, 101–109.

- ICCO (2022). International Cocoa Organization - Statistics. <https://www.icco.org/statistics/>. Last visited 2022-06-01.
- IISD (2009). Global Market Report: Cocoa. <https://www.iisd.org/ssi/publications/global-market-report-cocoa/>. Last visited 2022-06-01.
- IPCC (2007). Chapter 20: Perspectives on Climate Change and Sustainability - 20.6 Global and aggregate impacts. In *AR4 Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 811–841. Cambridge, UK: Cambridge University Press.
- IPCC (2022a). Chapter 2: Terrestrial and Freshwater Ecosystems and their Services. In *AR6 Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY, USA: Cambridge University Press.
- IPCC (2022b). Cross-Chapter Paper 7: Tropical Forests. In *AR6 Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY, USA: Cambridge University Press.
- IPCC (2022c). Summary for Policymakers. In *AR6 Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY, USA: Cambridge University Press.
- IWG (2021). Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide | Interim Estimates under Executive Order 13990. *Interagency Working Group on Social Cost of Greenhouse Gases, United States Government*, 48.
- Jayachandran, S., J. de Laat, E. F. Lambin, C. Y. Stanton, R. Audy, and N. E. Thomas (2017, July). Cash for carbon: A randomized trial of payments for ecosystem services to reduce deforestation. *Science* 357(6348), 267–273. Publisher: American Association for the Advancement of Science.
- Jones, S. and P. Gibbon (2011, October). Developing Agricultural Markets in Sub-Saharan Africa: Organic Cocoa in Rural Uganda. *Journal of Development Studies* 47(10), 1595–1618. Publisher: Routledge.
- Liang, Y., L. Liu, and J. Huang (2017, February). Integrating the SD-CLUE-S and InVEST models into assessment of oasis carbon storage in northwestern China. *PLOS ONE* 12(2), e0172494. Publisher: Public Library of Science.
- Luedeling, E., G. Sileshi, T. Beedy, and J. Dietz (2011, July). Carbon Sequestration Potential of Agroforestry Systems in Africa. In *Advances in Agroforestry*, Volume 8, pp. 61–83.

- Middendorp, R., V. Vanacker, and E. Lambin (2018, November). Impacts of shaded agroforestry management on carbon sequestration, biodiversity and farmers income in cocoa production landscapes. *Landscape Ecology* 33.
- Milder, J. C., M. Arbuthnot, A. Blackman, S. E. Brooks, D. Giovannucci, L. Gross, E. T. Kennedy, K. Komives, E. F. Lambin, A. Lee, D. Meyer, P. Newton, B. Phalan, G. Schroth, B. Semroc, H. V. Rikxoort, and M. Zrust (2015). An agenda for assessing and improving conservation impacts of sustainability standards in tropical agriculture. *Conservation Biology* 29(2), 309–320.
- Millennium Ecosystem Assessment (2005). *Ecosystems and human well-being: synthesis*. Washington, DC: Island Press. OCLC: ocm59279709.
- Mukono District LG (2015). District Development Plan 2015/2016 - 2019/2020. Technical report.
- Nair, R. P., B. Mohan Kumar, and V. Nair (2009, February). Agroforestry as a strategy for carbon sequestration. *Journal of Plant Nutrition and Soil Science* 172, 10–23.
- Nair, R. P., V. D. Nair, B. M. Kumar, and S. G. Haile (2009, December). Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. *Environmental Science & Policy* 12(8), 1099–1111.
- Nair, R. P., V. D. Nair, B. Mohan Kumar, and J. M. Showalter (2010, January). Chapter Five - Carbon Sequestration in Agroforestry Systems. In D. L. Sparks (Ed.), *Advances in Agronomy*, Volume 108, pp. 237–307. Academic Press.
- Natural Capital Project (s.d.). Carbon Storage and Sequestration — InVEST documentation. <http://releases.naturalcapitalproject.org/invest-userguide/latest/carbonstorage.html>. Last visited 2022-04-05.
- Nelson, V. and D. Phillips (2018). Sector, Landscape or Rural Transformations? Exploring the Limits and Potential of Agricultural Sustainability Initiatives through a Cocoa Case Study. *Business Strategy and the Environment* 27(2), 252–262.
- Nordhaus, W. D. (2017, February). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences* 114(7), 1518–1523. Publisher: Proceedings of the National Academy of Sciences.
- OEC (2020). Uganda (UGA) Exports, Imports, and Trade Partners. <https://oec.world/en/profile/country/uga/>. Last visited 2022-06-06.
- Preissel, S. and M. Reckling (2010, April). Smallholder group certification in Uganda - Analysis of internal control systems in two organic export companies. *Journal of Agriculture and Rural Development in the Tropics and Subtropics* 111, 13–22.
- Project, N. C. (2019, April). InVEST. <https://naturalcapitalproject.stanford.edu/software/invest>. Last visited 2022-04-05.

- Roshetko, J. M., R. D. Lasco, and M. S. D. Angeles (2007). Smallholder Agroforestry Systems For Carbon Storage. *Mitigation and adaptation strategies for global change*. Publisher: Dordrecht : Kluwer Academic Publishers.
- Rueda, X., A. Paz, T. Gibbs-Plessl, R. Leon, B. Moyano, and E. F. Lambin (2018). Smallholders at a Crossroad: Intensify or Fall behind? Exploring Alternative Livelihood Strategies in a Globalized World. *Business Strategy and the Environment* 27(2), 215–229. Publisher: Wiley Blackwell.
- Sanderman, J., T. Hengl, G. Fiske, K. Solvik, M. F. Adame, L. Benson, J. J. Bukoski, P. Carnell, M. Cifuentes-Jara, D. Donato, C. Duncan, E. M. Eid, P. z. Ermgassen, C. J. E. Lewis, P. I. Macreadie, L. Glass, S. Gress, S. L. Jardine, T. G. Jones, E. N. Nsombo, M. M. Rahman, C. J. Sanders, M. Spalding, and E. Landis (2018, April). A global map of mangrove forest soil carbon at 30\hspace0.167emm spatial resolution. *Environmental Research Letters* 13(5), 055002. Publisher: IOP Publishing. [Accessed on 2021-11-25 from Global Forest Watch].
- Tennhardt, L., G. Lazzarini, R. Weissshaidinger, and C. Schader (2022, July). Do environmentally-friendly cocoa farms yield social and economic co-benefits? *Ecological Economics* 197, 107428.
- The World Bank (2020). Population, total - Uganda. <https://data.worldbank.org/indicator/SP.POP.TOTL?end=2020&locations=UG&start=1960&view=chart>. Last visited 2022-04-04.
- Toledo-Hernández, M., T. C. Wanger, and T. Tscharncke (2017, September). Neglected pollinators: Can enhanced pollination services improve cocoa yields? A review. *Agriculture, Ecosystems & Environment* 247, 137–148.
- Tschora, H. and F. Cherubini (2020, June). Co-benefits and trade-offs of agroforestry for climate change mitigation and other sustainability goals in West Africa. *Global Ecology and Conservation* 22.
- Uganda Bureau of Statistics (2017). National Population and Housing Census 2014, Area Specific Profiles: Mukono District. Technical report, Mukono District - Local Government.
- Vaast, P. and E. Somarriba (2014, December). Trade-offs between crop intensification and ecosystem services: the role of agroforestry in cocoa cultivation. *Agroforestry Systems* 88(6), 947–956.
- Wang, P., X. Deng, H. Zhou, and S. Yu (2019, February). Estimates of the social cost of carbon: A review based on meta-analysis. *Journal of Cleaner Production* 209, 1494–1507.
- Woomer, P. L., C. A. Palm, J. N. Qureshi, and J. Kotto-Same (1998). Carbon Sequestration and Organic Resource Management in African Smallholder Agriculture. In *Management of Carbon Sequestration in Soil*. CRC Press. Num Pages: 21.
- WRI (2009). Uganda: Linking Wetlands and Sanitation in the Sezibwa Wetland System. <https://www.wri.org/data/uganda-linking-wetlands-and-sanitation-sezibwa-wetland-system>. Last visited 2022-05-30.

Zhang, F., J. Zhan, Q. Zhang, L. Yao, and W. Liu (2017, October). Impacts of land use/cover change on terrestrial carbon stocks in Uganda. *Physics and Chemistry of the Earth, Parts A/B/C 101*, 195–203.

List of Figures

3.1	Study area (represented by a red polygon). Main river and district information in the lower left section, and real colors Landsat 8 (band 4,3,2) image (March 2019) in the lower right section. Location of the study area in Uganda upper left section and in Mukono District upper right section. Data sources: Landsat 8 image (United States Geological Survey Earthexplorer portal); Sampled smallholders (Tennhardt, 2022).	16
3.2	Detailed topographical map of Uganda. Study area represented by a red polygon inside Uganda's limits. Source: Maplands, s.d.	17
4.1	Land Use Land Cover classification map, based on 2019 Landsat 8 image.	23
4.2	Hypothetical extreme future Land Use Land Cover classification map. Calendar year to reach it varies through the scenarios, respectively being 2024, 2029, 2034 and 2039.	24
4.3	Boxplots of the extraction carbon pool values for each class. Aboveground biomass on the left and soil organic carbon on the right. 1 = vegetated wetlands, 2 = non-vegetated wetlands, 3 = agroforestry systems, 4 = classical agricultural systems.	25
4.4	Map of the current (2019) carbon storage of the study area assessed by the InVEST model. Units are in MgC ha^{-1}	27
4.5	Map of the future situation carbon storage of the study area assessed by the InVEST model. Units are in MgC ha^{-1}	29
4.6	Map of the additional storage of carbon between the current and the future situations. Units are in MgC ha^{-1}	30
4.7	Summary plot of the stored carbon per class for the current and future situations. 'Delta total carbon' corresponds to the sequestered carbon between both situations.	30
4.8	Boxplots of the total and land uses areas per farm, expressed in hectares (ha).	33
4.9	Boxplots of the land use ratios per farm (expressed in % of the total area).	33

4.10	Boxplot of the ratio of the farm area under agroforestry (on the left) and correlation plot (+ trend line in red) with the farm area (on the right).	34
4.11	Boxplot of the ratio of the farm area dedicated to cocoa cultivation (on the left) and correlation plot (+ trend line in red) with the farm area (on the right).	34
4.12	Relation between the agroforestry surface ratio and the cocoa surface ratio of the farms. Red observations concern the values for which the difference in absolute values between the ratios of the two variables is $<$ or $= 0.01$	37
5.1	Production Operating Cost Estimate - <i>Eucalyptus</i> . Concerning the assessment of land use/cover changes and carbon dynamics at farm level in a Brazilian area. "Scenario 3" refers to forest plantation and "Scenario 4" refers to silvopastoral system implementation. Source: Dargains and Cabral (2021)	44
5.2	Model linear carbon sequestration path vs. actual nonlinear carbon sequestration path. Source: Natural Capital Project (sd)	48
1	Trade flows of the largest producer countries in 2016, in metric tons. These five countries represents the 80 per cent of total cocoa production in 2016. The % in brackets for each country represents the proportion of the total volume of cocoa exported in 2016 by the five countries. The % in brackets for each region represents the proportion of the total volume of cocoa imported in 2016 from the 5 countries. Source : International Institute for Sustainable Development (IISD, 2009).	61
3	Wetness index. Elaboration with the Landsat-8 imagery bands, following: (Band 5–Band 6)/(Band 5+Band 6).	63
2	Elements of interest : permanent and seasonal wetlands. Red polygon on the upper right map shows the approximate study area. Source : World Resources Institute (WRI, 2009)	64
4	Factors determining the economic potential of agroforestry systems to sequester carbon. Source: Luedeling et al. (2011)	65
5	Schematic illustration of the different types of carbon sequestration potentials, and the constraints that are encountered in their quantification. Source: Luedeling et al. (2011)	65

List of Tables

4.1	Accuracy assessment results from the current LULC classification map.	22
4.2	Main statistics of the carbon pools storage value extraction by LULC class expressed in MgC ha ⁻¹ and area (in ha) of each LULC class. AGB = aboveground biomass. .	25
4.3	Wilcoxon test statistics for each combination, and its associated <i>p</i> -values. H0 : $\mu_1 = \mu_2$. * = significance considering $\alpha = 0.05$	26
4.4	Carbon pools input table required by the InVEST model, expressed in MgC ha ⁻¹ . C_above = carbon density of aboveground biomass ; C_below = carbon density of belowground biomass ; C_soil = carbon density of soil ; C_dead = carbon density of dead matter.	26
4.5	InVEST model's estimation of the stored carbon values per class for the current situation. Units are in MgC ha ⁻¹ (except for the total stored carbon of the whole study area).	28
4.6	InVEST model's estimation of the stored carbon values per class for the future situation. Units are in MgC ha ⁻¹ (except for the total stored carbon of the whole study area and the net difference)..	29
4.7	Carbon sequestration rates following the different scenarios. Units are in MgC ha ⁻¹ yr ⁻¹	31
4.8	Economic valuation (\$US) of the change from classical agricultural system to agro-forestry system for the different scenarios.	31
4.9	Main statistics of the economic valuation per farm. Units of the Total, Per year, and Per month are in US\$.	36
4.10	Table of the mean valuation per farm based on the area statistics of the surveyed farms. Units of the Total, Per year, and Per month are in US\$.	37
1	Review of existing carbon stock assessments of certain regions, under certain systems. The first source cited refers to the paper in which data has been found, if second source is cited it refers to reference mentioned by the first one.	62

2	Table of the most produced commodities for 2020 in Uganda. Source: FAOSTAT (2022)	63
---	---	----

Appendix

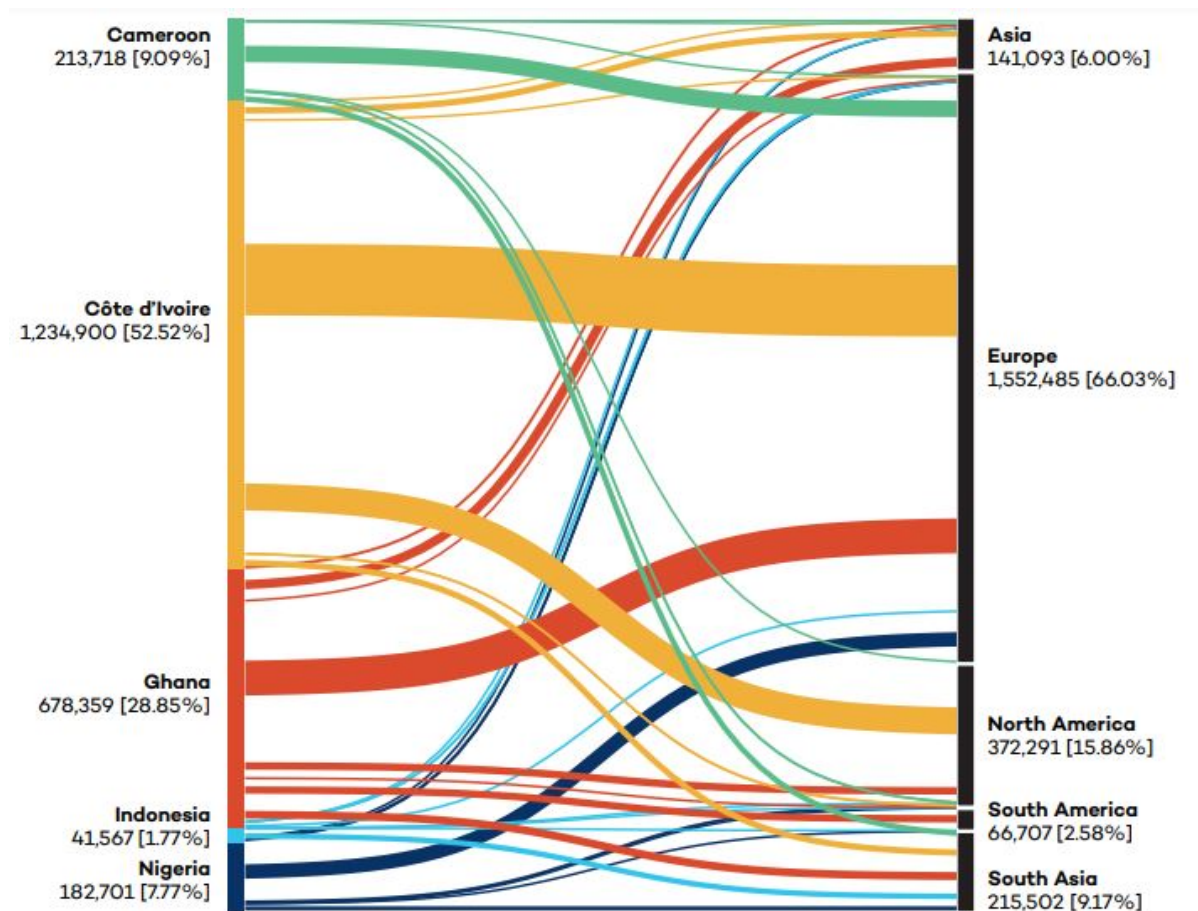


Figure 1: Trade flows of the largest producer countries in 2016, in metric tons. These five countries represents the 80 per cent of total cocoa production in 2016. The % in brackets for each country represents the proportion of the total volume of cocoa exported in 2016 by the five countries. The % in brackets for each region represents the proportion of the total volume of cocoa imported in 2016 from the 5 countries. Source : International Institute for Sustainable Development ([IISD, 2009](#)).

Table 1: Review of existing carbon stock assessments of certain regions, under certain systems. The first source cited refers to the paper in which data has been found, if second source is cited it refers to reference mentioned by the first one.

Region	Carbon stock (MgC ha ⁻¹)	Type	Source	Comment
Agroecological zone : Tropical highlands	21-97	Soil carbon stock	Nair et al., 2009 (based on literature)	Shaded perennial systems. Depth not specified
	100–200 / 20–50.	Soil carbon stock / potential for sequestrating additional carbon	Nair et al., 2009 (based on literature)	Shaded perennial systems, age = 15yr or older, soil carbon stock depth = 50 cm, potential for sequestrating soil depth : 100cm, time frame for realizing the potential = 10 yr.
	70–150 / 100–250	Soil carbon stock / potential for sequestrating additional carbon	Nair et al., 2009 (based on literature)	Shaded perennial systems, age = 6yr or younger, soil carbon stock depth = 50 cm, potential for sequestrating soil depth : 100cm, time frame for realizing the potential = 10 yr.
	302	Soil carbon stock	Nair et al., 2010 (Gama-Rodrigues et al., 2010)	Shaded cacao systems, age = 30yr, soil depth = 0-100cm
Bahia, Brazil				
Mekoe, Cameroon	20.5	Root carbon stock	Nair et al., 2009 (Duguma et al., 2001)	Cacao agroforests : Cacao (Theobroma cacao) in mixed stands, plantation age 26,
	145	Aboveground carbon stock	Nair et al., 2009 (Duguma et al., 2001)	Cacao agroforests : Cacao (Theobroma cacao) in mixed stands, plantation age 26,
Ecoregion : Humid tropical high, Africa	29-53	Agroforestry systems carbon stock	Albrecht et al., 2003 (based on literature)	System=agrosilvicultural
Southwestern Togo	97.3	Soil carbon stock	Nair et al., 2010 (Dossa et al., 2008)	Shaded coffee (Coffea robusta L.), age = 13yr, soil depth = 0-40 cm
	87.7	Above and below-ground carbon stock	Tschora et al., 2020	Average carbon stock of shaded cocoa (from agroforestry) (plot scale)
	83.7 ± 7.0	Above and below-ground carbon stock	Tschora et al., 2020	Average carbon stock of shaded agroforestry trees (plot scale). Large variability across plots (21 to 224)
West African Sahel countries (from arid Sahara desert to humid region Guinea)	22.2-70.8	Tree biomass held by trees	Humphrey et al., 2017 (Luedeling et al., 2012)	Agroforestry (type not specified)

Table 2: Table of the most produced commodities for 2020 in Uganda. Source: [FAOSTAT \(2022\)](#)

Item	Value (tons)
Fruit Primary	7457778
Plantains and others	7401579
Roots and Tubers, Total	6053251
Sugar cane	5778187
Sugar Crops Primary	5778187
Cassava	4207870
Cereals, Total	3436305
Maize	2750000
Milk, Total	1766386
Milk, whole fresh cow	1766386

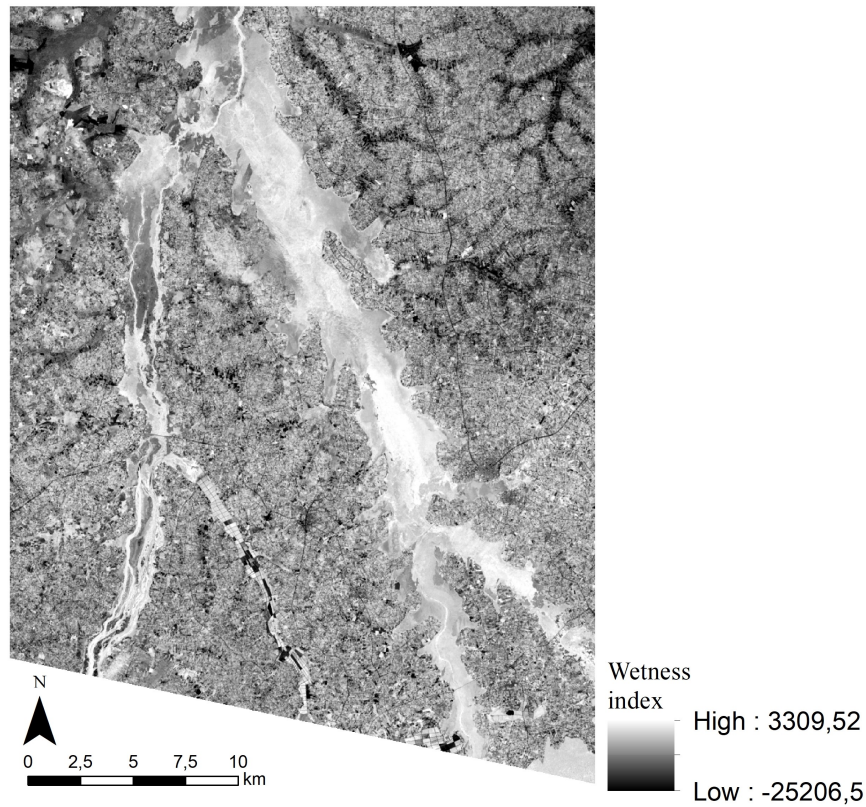


Figure 3: Wetness index. Elaboration with the Landsat-8 imagery bands, following: $(\text{Band } 5 - \text{Band } 6) / (\text{Band } 5 + \text{Band } 6)$.

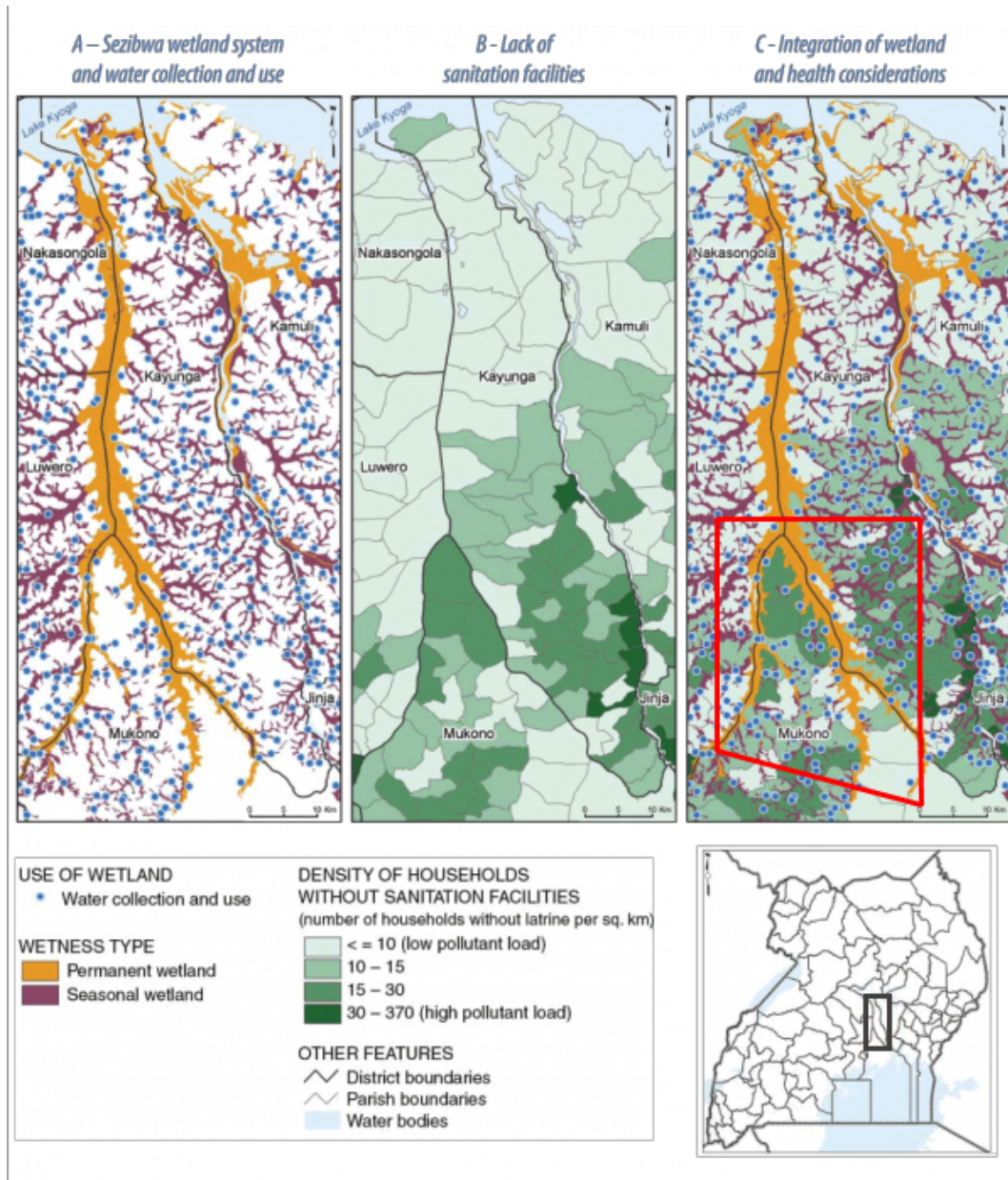


Figure 2: Elements of interest : permanent and seasonal wetlands. Red polygon on the upper right map shows the approximate study area. Source : World Resources Institute ([WRI, 2009](#))

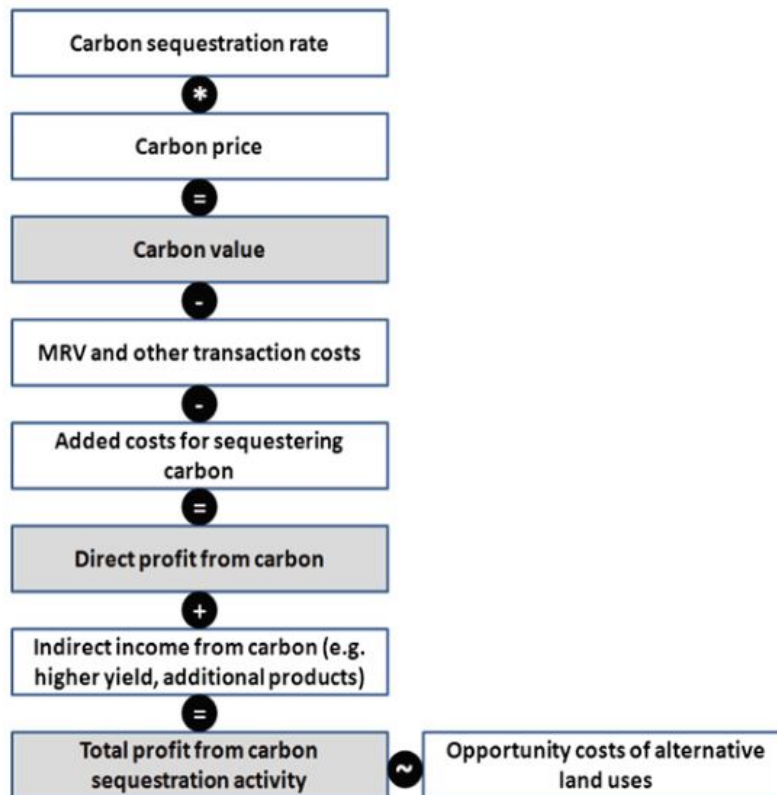


Figure 4: Factors determining the economic potential of agroforestry systems to sequester carbon. Source: [Luedeling et al. \(2011\)](#).

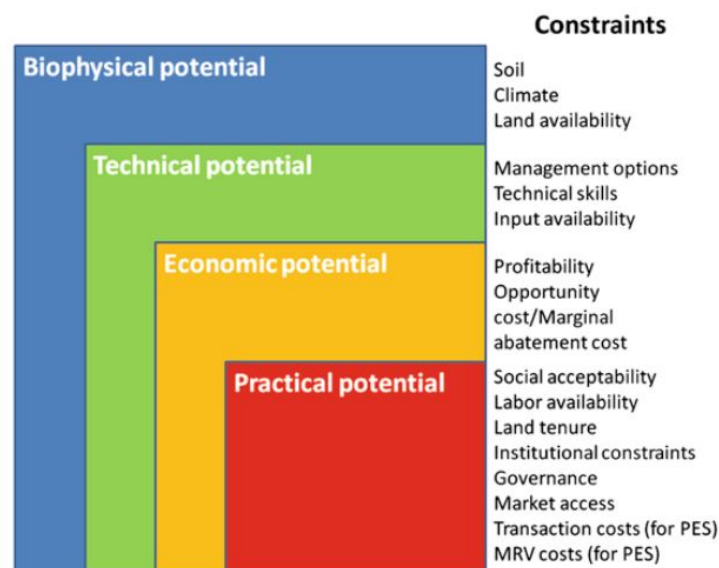


Figure 5: Schematic illustration of the different types of carbon sequestration potentials, and the constraints that are encountered in their quantification. Source: [Luedeling et al. \(2011\)](#)

Biography

I did most of my primary schooling at the Sacré Coeur de Lindthout school (Brussels), in the middle of which I spent a few years in Sydney (Australia). In high school, I was at the Collège Saint-Michel (Brussels). After a gap year in Argentina, in 2017 I started a bachelor in Geographical Sciences, at the Université Catholique de Louvain-la-Neuve (UCLouvain) from which I graduated in 2020. This same year I started a master in Geography, general orientation with a research focus.

Julie Hernandez

Avenue Voltaire 40, 1030, Brussels

juju.hernandez@gmail.com

