Carbon sequestration potential of parkland agroforestry in the Sahel

Eike Luedeling · Henry Neufeldt

Abstract Establishing parkland agroforestry on currently treeless cropland in the West African Sahel may help mitigate climate change. To evaluate its potential, we used climatically suitable ranges for parklands for 19 climate scenarios, derived by ecological niche modeling, for estimating potential carbon stocks in parkland and treeless cropland. A biocarbon business model was used to evaluate profitability of hypothetical Terrestrial Carbon Projects (TCPs), across a range of farm sizes, farm numbers, carbon prices and benefit sharing mechanisms. Using climate analogues, we explored potential climate change trajectories for selected locations. If mature parklands covered their maximum range, carbon stocks in Sahelian productive land would be about 1,284 Tg, compared to 725 Tg in a treeless scenario. Due to slow increase rates of total system carbon by 0.4 Mg C ha^{-1} a^{-1}, most TCPs at carbon prices that seem realistic today were not feasible, or required the participation of large numbers of farmers. For small farms, few TCP scenarios were feasible, and low Net Present Values for farmers made it unlikely that carbon payments would motivate many to participate in TCPs, unless additional benefits were provided. Climate analogue locations indicated an uncertain climate trajectory for the Sahel, but most scenarios projected increasing aridity and reduced suitability for parklands. The potentially severe impacts of climate change on Sahelian ecosystems and the uncertain profitability of TCPs make the Sahel highly risky for carbon investments. Given the likelihood of degrading environmental conditions, the search for appropriate adaptation strategies should take precedence over promoting mitigation activities.

1 Introduction

Recent increases in atmospheric greenhouse gas concentrations appear to be altering the global climate, and future projected increases are expected to continue this trend (IPCC

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2007). An important strategy for slowing anthropogenic climate change is sequestration of carbon dioxide from the atmosphere (Paustian et al. 1998; Thomson et al. 2010) by raising the carbon stocks of landscapes (Dumanski et al. 1998; Smith et al. 2008).

Establishing agroforestry on land that currently has low tree cover has been identified as one of the most promising strategies to raise carbon stocks on currently productive land without compromising food and fiber production (Albrecht and Kandji 2003; Kuersten and Burschel 1993; Montagnini and Nair 2004). Agroforestry is the deliberate integration of trees or other woody perennials into field crop or livestock systems, in order to exploit synergies and complementarities between different structural elements of the system. Agroforestry has been shown in many instances to lead to more diverse, more productive and more sustainable agricultural production than less integrated approaches (e.g. Cannell et al. 1996; Nair 2007; Sinclair 1999; Van Noordwijk and Lusiana 1998).

Carbon stock increases resulting from conversion of treeless land to agroforestry have been estimated at 3 Mg C ha^{-1} a^{-1} in tropical regions (IPCC 2000). Conversion of agricultural land to agroforestry has also been reported to entail substantial co-benefits for farmers, such as enhanced soil fertility, resilience to weather extremes and additional sources of farm income (Ajayi et al. 2007; Garrity 2004; Sanchez 1995). Tree-based agricultural systems in many parts of the world have been shown to have higher carbon stocks than treeless farming systems (Luedeling et al. 2011; Nair et al. 2009a, b) and to provide more environmental services (Jose 2009; Paustian et al. 1998).

Global carbon markets have opened up the possibility of payments to farmers for their contribution to climate change mitigation (Jose 2009). Although to date few carbon finance projects have focused on agroforestry, the volume of the combined compliance and voluntary markets in the forestry sector reached 30.1 MtCO$_2$-eq with a value of over US$133 million in 2010, and market trends promise further growth (Diaz et al. 2011). Since other environmental services are increasingly included in carbon projects, agroforestry is becoming an attractive option for Terrestrial Carbon Projects (TCPs). Wendland et al. (2010) present a method for identifying promising areas for carbon projects in Madagascar that may also attract payments for biodiversity preservation. Milder et al. (2010) also highlight the potential for farmers to receive payments for non-carbon ecosystem services, which could be combined with carbon payments in order to make additional activities economically attractive.

Agroforestry systems in humid tropical regions can store substantial amounts of carbon, but little attention has been paid to potential carbon stocks in drier areas. Only Smith et al. (2008) provide an estimate for agroforestry in warm dry areas (at −0.73–1.39 Mg C ha^{-1} a^{-1}, with a mean of 0.33 Mg C ha^{-1} a^{-1}), but these numbers were produced by assuming that agroforestry sequestered the same amount of carbon as agriculture with tillage and residue management. They considered only soil carbon and did not take into account above and belowground carbon sequestered in the trees. These numbers are thus unlikely to reflect the true potential of dryland agroforestry systems.

Another knowledge gap concerns the potential for smallholder farmers in dry areas to receive payments for planting trees via carbon markets. While some agroforestry carbon projects have been started in more humid areas, the economic viability of TCPs focusing on Sahelian parklands has never been explored.

This paper focuses on the traditional parklands of the West African Sahel (Bayala et al. 2002; Kho et al. 2001). This agroforestry system mimics the natural savannah (van Noordwijk and Ong 1999) by preserving mature trees of a range of species, among which annual crops are planted. Kindt et al. (2008) identified 110 tree species in Sahelian parklands, including *Adansonia digitata* L., *Faidherbia albida* (Delile) A.Chev., *Guiera senegalensis* J.F.Gmel.

and *Vitellaria paradoxa* C.F.Gaertn. Typical field crops are millet (*Pennisetum glaucum* (L.) R.Br.), sorghum (*Sorghum bicolor* (L.) Moench), maize (*Zea mays* L.), groundnut (*Arachis hypogaea* L.) and cowpea (*Vigna unguiculata* (L.) Walp.). Grazing cattle, goats and sheep are also common in these systems. TCPs aiming to sequester carbon by establishing parklands would require participating farmers to plant trees on their cropland, or to promote natural regrowth of trees. Where TCPs also aim to alleviate poverty, such activities should preferably be carried out by small subsistence farmers.

The objective of this study is to close these knowledge gaps. We present a regional-scale estimate of the potential of Sahelian parklands to sequester carbon, and a projection of likely climate change impacts on the Sahel's capacity to sustain parkland agroforests. In addition to this regional approach, we explore the economics of hypothetical TCPs, both from the project management and from the farmer perspective, and discuss the potential of such projects to alleviate poverty among smallholder farmers. Finally, we use climate analogue analysis to explore the potential of three important parkland regions in the Sahel to sustain this type of agroecosystem in a range of future climate scenarios.

2 Materials and methods

2.1 Potential areas for parkland agroforestry

The extent of agroforestry parklands in the Sahel has never been mapped, and little information is available on the climatic and environmental requirements of such systems. Due to the paucity of data, we used the maximum entropy (MaxEnt) ecological niche modeling approach (Phillips et al. 2006) to estimate potential parkland areas. This approach is commonly used to model the distribution of plant or animal species, based on known geographic positions where the species or ecosystem of interest occurs, and on environmental data layers that are used to characterize the habitat at these locations (e.g. Hernandez et al. 2006; Hijmans and Graham 2006; Pearson et al. 2007; Phillips and Dudík 2008). The MaxEnt method then assigns suitability scores to all grid cells within the study extent, based on environmental requirements of the species obtained from the input data. These scores express the potential of any point in the study area to sustain the species or ecosystem of interest. In this study, we applied the MaxEnt method to estimate suitable habitat for parkland agroforestry systems across the drier part of West Africa. We obtained a total of 101 reported occurrences of parklands from 18 published references (Bayala et al. 2006; Bayala et al. 2004; Bouvet et al. 2004; Deans and Munro 2004; Gijsbers et al. 1994; Kater et al. 1992; Kelly et al. 2004; Kho et al. 2001; Kindt et al. 2008; Maranz et al. 2004; Odebiyi et al. 2004; Reij et al. 2005, 2009; Takimoto 2007; Tilander et al. 1995; Timmer et al. 1996; Traore et al. 2004; Tschakert 2004). These 101 point locations were distributed throughout the Sahelian and Sudanian climate zones, while no sites from the moister Guinea savannah region were included. Even though the latter zone also has productive parklands, this zone was excluded to preserve the focus on dryland agroforestry systems. Environmental data layers were mean precipitation and mean daily temperature extremes for all months of the year, obtained from the WorldClim database (Hijmans et al. 2005). Based on the MaxEnt suitability scores (ranging from 0 = unsuitable to 1 = optimal), we interpreted all areas with scores of 0.2 or higher as suitable for parkland agroforestry. Since this threshold placed 99 out of 101 reported parkland occurrences in suitable areas (Fig. SF1 in the Supplementary Materials), it was accepted for determining suitability for parklands in areas where no information on the presence or absence of this ecosystem was available. We then confined

the assessment to all areas classified as agriculturally productive land in 2000, according to a 2-km resolution dataset on land use in West Africa (Reij et al. 2009; US Geological Survey 2007). Besides climatic conditions, existence of parklands depends also on other factors, such as farmer decisions about preserving or removing parkland species on their farms. Nevertheless, there is likely a climatic zone, in which maintaining parklands is agronomically reasonable, and farmers will decide to preserve trees predominantly in this zone. We therefore used only climatic parameters for modeling suitability for parklands.

2.2 Potential carbon stocks

We found only three studies that have compared parkland systems with cultivated land (Tab. ST1 of the Supplementary Materials). Takimoto et al. (2008) investigated carbon stocks in five different land use systems in the Ségou region of Mali, including parklands and two recently established types of agroforestry (fodder bank and live fences). Since this study did not include a treeless baseline, we used the two recently established agroforestry systems as a substitute. This approach seemed acceptable, because above-ground C stocks in these systems were very low compared to parklands and also compared to soil carbon. Woomer et al. (2004) analyzed terrestrial carbon stocks in various environments of Senegal, including parkland and cultivated land in the Drier Sudanian Woodland of the Old Peanut Basin and the Sudano-Guinean Transition zone. Tschakert (2004) focused on parkland systems in the Old Peanut Basin, providing carbon stock estimates for 21 sites, 18 of which could be classified as parkland or cultivated land. Estimates of combined carbon stocks in trees, shrubs and the upper 40 cm of the soil for each study were used for further considerations. For each study, all carbon stock estimates for parkland and for cultivated land were averaged, and these were then averaged over all three studies. The scarcity of available data did not allow differentiation by soil type or environmental conditions. Total carbon stocks in treeless cropland and parkland were then estimated by multiplying potential areas and carbon stocks per area.

2.3 Annual carbon sequestration rates and TCP economics

Converting potential carbon stocks into C sequestration rates requires knowledge of the time needed to reach the potential. Long-term observations of C stock increments over several decades are not available, but Tschakert (2004) used the CENTURY carbon flux model to estimate carbon dynamics of a *Faidherbia albida* plantation established on cultivated land in Senegal that was formerly covered by savannah vegetation. Carbon levels declined dramatically at the onset of cultivation and still had not fully recovered 50 years after establishment of the plantation. Takimoto et al. (2008) dated the establishment of parklands in Mali to at least 35 years ago. We adopted 50 years as a reasonable estimate of the time to reach maximum carbon stocks.

    Besides the carbon sequestration rate, the economics of Terrestrial Carbon Projects (TCPs) depend on a range of other factors, such as the costs of project management, monitoring, reporting and verification of sequestered carbon (MRV). High costs can easily render a project infeasible even if carbon benefits are large on the landscape scale. We modeled TCP economics using a financial carbon accounting tool used by practitioners for planning TCPs (Tanja Havemann, pers. comm.). The tool was developed for a CARE Agriculture, Forestry and Other Land Use (AFOLU) project in western Kenya (CARE 2011), and adjusted to fit price structures in the Sahel (Antoine Kalinganire, pers. comm.; Table 1). To test whether TCPs could provide benefits for resource constrained farmers, we compared their performance across different land holding sizes, with average areas of new

Table 1 Parameters used for the hypothetical Terrestrial Carbon Projects in the Sahelian parklands

Parameter		Values
Farm size scenarios (parkland area)		2, 4, 6, 8 and 10 ha
Discount rate		12 %
Trees planted per hectare		200
Sequestration rate per year		1.47 Mg CO_2ha^{-1}
MRV	Mapping (once)	US$20,000 + US$0.5 per farm
	Monitoring (per year)	US$20,000 + US$0.5 per farm
	Verification (per 5 years)	US$20,000 + US$0.5 per farm
Staff	Project manager	1
	Extension workers	1 per 2,000 farms (rounded up to next integer)
Staff cost	Project manager	US$15,000 per year (+10 % overhead)
	Extension workers	US$1,600 per year (+10 % overhead)
	Training	US$1,000 per year
Travel expenses		US$2 per farm
Vehicles	number of cars [a]	1 per 50,000 farms (rounded up to next integer)
	number of motorcycles [b]	1 per 2,000 farms (rounded up to next integer)

[a] Purchase costs: US$30,000; vehicle life: 5 years; re-sale value: US$5,000; operating costs: US$6,500 p.a.

[b] Purchase costs: US$3,000; vehicle life: 3 years; re-sale value: US$1,000; operating costs: US$1,000 p.a.

parklands of 2, 4, 6, 8 and 10 ha. Average farm size in the Sahel is around 5 ha in parkland regions of Senegal (Stéphenne and Lambin 2001) and Burkina Faso (Reij et al. 2009), so that this set of sizes should be representative of the range of farm sizes among small and medium-sized Sahelian farmers. Two-hectare farms likely represent the smallest, and likely poorest, landholders, whereas the high end of the farm size spectrum should describe the largest farms of a typical village community. The main outputs of the model are the amount of carbon dioxide sequestered in woody biomass or soil and the Net Present Value (NPV) of the operation, both for the project managers and for individual farmers. The NPV is the sum of all revenue over the 25-year life span of the project, with each year's revenue divided by $(1 + dr)^a$. In the equation, dr is the discount rate and a the year after project inception, in which the revenue is accrued. We used a discount rate of 12 %, which is typical for decisions by businesses on long-term investments in developing countries.

We simulated two different benefit sharing mechanisms, resembling two farmer compensation structures currently existing in Kenya. Payment option 1 (P30 %) assumes that farmers receive 30 % of gross income from carbon sales every 5 years, which is typical of many projects approved by the Verified Carbon Standard (VCS 2011). Payment option 2 (P0.02) assumes a payment of $0.02 annually for each existing tree, similar to the approach taken by the International Small Group and Tree Planting Program (TIST; www.tist.org). We ran the model for a number of combinations of farm size, payment option, carbon price and numbers of farms in the project to gain understanding about the framework that must exist for TCPs in the Sahel to be viable.

2.4 Climate analogues and future suitability

The climate analogue approach follows the premise that most projections of the climate at a given location correspond to climate that is currently observed somewhere else. Given

sufficient similarity of other environmental factors, the ecosystems that exist at the analogue location at present can be used to visualize climate change impacts at the target location. We determined climate analogues based on baseline (1950–2000 from WorldClim; Hijmans et al. 2005) climate conditions and projected conditions for three global climate models (CSIRO, HADCM3 and CCCMA), two greenhouse gas emissions scenarios (A2a and B2a) and three points in time (2020s, 2050s and 2080s) (CCAFS Downscaled GCM Data Portal; http://www.ccafs-climate.org). Climate variables used were mean precipitation and mean daily temperature extremes for all months of the year. The search for climate analogues was confined to Africa, for which all climate data layers were resampled to a spatial resolution of one sixth of a degree.

Climate analogues were determined for three exemplary sites in the Sahel: the Old Peanut Basin in Senegal (represented by the data point 14.8°N; −16.7°E), Ségou, Mali (13.4°N; −6.3°E) and Zinder, Niger (13.8°N; 9.0°E). Table ST2 of the Supplementary Materials summarizes changes in mean annual precipitation and mean daily temperature extremes for all climate models for the three sites. For each of the three locations, we first obtained projected climate conditions for all 18 climate scenarios. For each scenario and each site, all 36 climate variables (monthly Tmin, Tmax and precipitation) were then compared with conditions in all grid cells of the baseline scenario, using a Euclidean distance approach:

$$\text{Climatic distance} = \sqrt{\sum_{par} \sum_{m} w_{par,m} \cdot \left(\frac{P_{par,m} - F_{par,m}}{norm_{par}} \right)^2},$$

in which *par* is the array of weather parameters, *m* is the list of all months in the year, $w_{par,m}$ is a weighting factor (specific to weather parameter and month; set to 1 for temperature variables and 2 for precipitation), $P_{par,m}$ and $F_{par,m}$ are the values of the respective parameter for the present and future scenarios, and $norm_{par}$ is a normalization parameter, set to the interquartile range of the distribution of the respective monthly values in the entire Africa-wide population of grid cells. Since the climate analogue approach has not yet been widely used, there is no guidance on how to select optimal values for weighting different climate metrics. Weights were thus chosen based on our intuition, placing twice as much importance on precipitation as on the temperature parameters.

The climatic distance is a good measure for the similarity between projected climate at the target site and the current climate of any other location. The grid cell, for which the distance measure was minimized, was identified as the best currently existing climate analogue of the sample location for the respective climate scenario. The 50 closest analogue locations were also identified. All analysis steps were implemented in R programming language.

2.5 Evaluation of climate analogues

Monthly climate information of the baseline scenario was processed into a simple aridity index consisting of precipitation divided by potential evapotranspiration (PET). Expressing rainfall as a fraction of the amount of water that could potentially be evaporated by soils or transpired by plants allows for classification of environments into aridity zones. For this index, PET was estimated separately for each month of the year (represented by the 15th day of the month) using the Hargreaves equation (Hargreaves et al. 1985; implemented in ArcGIS model builder). Temperature inputs for this equation were calculated from the WorldClim temperature layers, whereas extraterrestrial radiation was calculated according to Allen et al. (1988). For all climate analogues identified for the three sites and for the 50

closest analogues, the aridity index was sampled allowing a comparison of current and projected future aridity at the site. Future suitability of the three sample locations for parklands was explored by extracting MaxEnt suitability scores for the same locations.

2.6 Climate change impacts on potential carbon stocks

While expansion of parklands can raise regional-scale carbon stocks, the impact of climate change may lower carbon stocks. Ecological niche modeling allows projection of the extent and location of ecological niches for future climate scenarios, provided that all data layers used for characterizing the niche are also available for future scenarios. We determined MaxEnt scores for all 18 future scenarios (from WorldClim; Hijmans et al. 2005), and summarized potential parkland areas for all scenarios. We then used the same conversion factors as outlined above for calculating potential carbon stocks in cultivated land for two scenarios: 1) no parkland and 2) parklands cover the maximum extent possible. Lacking reliable data on future land use, we assumed in this calculation that the area covered by cultivated land will remain unchanged.

3 Results

3.1 Potential parkland area and carbon stocks

Within the study extent, all but the transition zone towards the arid Sahara Desert and the more humid region of Guinea were classified as climatically suitable for parkland agroforestry (Fig. 1), indicated by MaxEnt suitability scores of 0.2 or higher. Of the 36.1 million ha classified as agricultural land in the land use dataset, 77.2 % were classified as suitable for parkland agroforestry (Table 2).

Among the three studies analyzed, carbon stocks ranged from 12.7 to 59.3 Mg C ha^{-1} for treeless croplands, and from 22.2 to 70.8 Mg C ha^{-1} for parkland (Tab. ST1). Since data scarcity did not allow including the environmental and management differences causing this variation, we only used average carbon stocks of 26 Mg C ha^{-1} in treeless cropland and
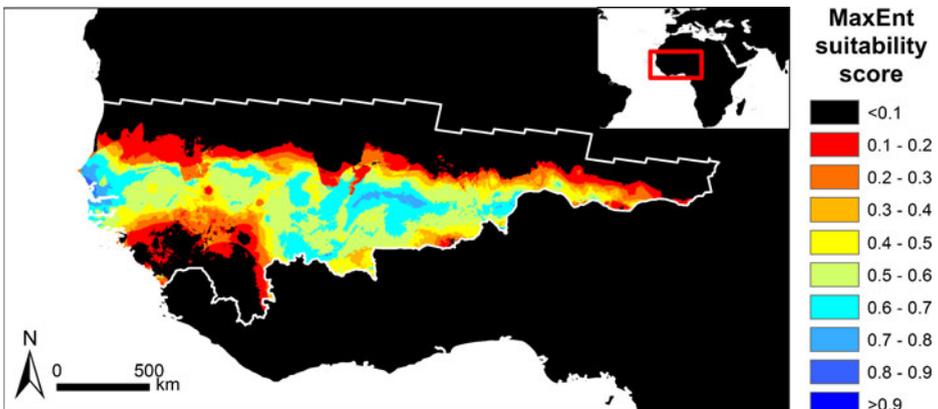
Fig. 1 MaxEnt suitability scores for parklands in West Africa, based on 101 published parkland locations and 36 monthly climate layers. High scores indicate suitability for parklands. The *white line* delineates the study extent

Table 2 Suitability of Sahelian cropland (absolute and as share of total cropland) for parkland agroforestry, according to suitability classes based on MaxEnt scores	Suitability class	Cultivated area (km²)	Share of cultivated area (%)
	Suitable for parkland (≥0.2)	279,020	77.2
	Unsuitable for parkland (<0.2)	82,265	22.8
	Total	361,285	100.0

46 Mg C ha^{-1} in parklands, indicating that parklands stored 20 Mg C ha^{-1} more than treeless cropland. Under the assumption that these estimates are representative of treeless agricultural land and parkland systems throughout the Sahel, potential carbon stocks can be estimated by multiplication of suitable or unsuitable areas and carbon stock per unit area. Such multiplication indicated total carbon stocks for the 'treeless agriculture' and 'maximum parkland' scenarios of 725 and 1,283 Tg C, respectively. Compared to treeless agriculture, the maximum parkland scenario would thus contain an additional 558 Tg C, corresponding to 2.05 Pg of sequestered CO_2.

3.2 Annual carbon sequestration rates and financial benefits

Dividing the potential C sequestration (20 Mg C ha^{-1}) by the accumulation time (50 years) resulted in a mean sequestration rate of 0.4 Mg C ha^{-1} a^{-1}, corresponding to 1.47 Mg ha^{-1} a^{-1} of sequestered CO_2. Assuming C sequestration at this constant rate in the simulation of TCP economics, a 100,000-farm project, with an average new parkland area of 10 ha per farm was able to sequester 28.8 Tg of CO_2 over 25 years (Fig. SF2 of the Supplementary Materials). If the same project targeted smallholders (2 ha of new parkland), only 5.8 Tg of CO_2 were sequestered.

The number of farms needed to make a TCP viable depended on the price of carbon, the parkland area per farm and the payment scheme. For all combinations of carbon payment scheme and farm size, projects were not viable for carbon prices below a defined threshold price (Fig. 2). For TCPs using the P0.02 payment scheme, threshold prices ranged from US $10.3 per Mg CO_2-eq for 10-ha farms to US$15.5 per Mg CO_2-eq for a project focusing on 2-ha farms. In the P30 % scenario, threshold prices were between US$2.7 and US$ 10.5 per Mg CO_2-eq (Fig. 2).

The Net Present Value of the TCPs depended on the number of farms enrolled, their sizes, the price of carbon and the payment scheme (Fig. 3). When using the P30 % scheme and targeting farmers with 6 or more ha of new parkland, NPV was positive, even at a low carbon price of US$5 per Mg CO_2-eq, and profit margins were high at carbon prices >US $10 per Mg CO_2-eq and for projects including at least 50,000 mid-sized farms (4 ha or more). Projects focusing on smallholders (2 ha of new parklands) were only successful at high carbon prices, and generated much smaller NPVs than projects targeting larger farms.

TCPs using the P0.02 payment scheme, selling carbon at US$20 per Mg CO_2-eq and targeting 10,000 or more farmers generated sizeable profits. However, at half the carbon price, closer to current values, project NPVs were negative for all scenarios (Fig. 3). At carbon prices exceeding US$30 per Mg CO_2-eq, the P0.02 payment scheme consistently generated higher NPVs than the P30 % scheme.

Farmer NPV depended entirely on farm size, if the TCP applied payment scheme P0.02 (Fig. 4). For smallholder farmers with 2 ha of new parkland, NPV was US$70.75, compared with US$353.74 for large holdings (10 ha). If payment scheme P30 % was used, NPV depended also on the price of carbon, and exceeded those in the P0.02 scheme at carbon
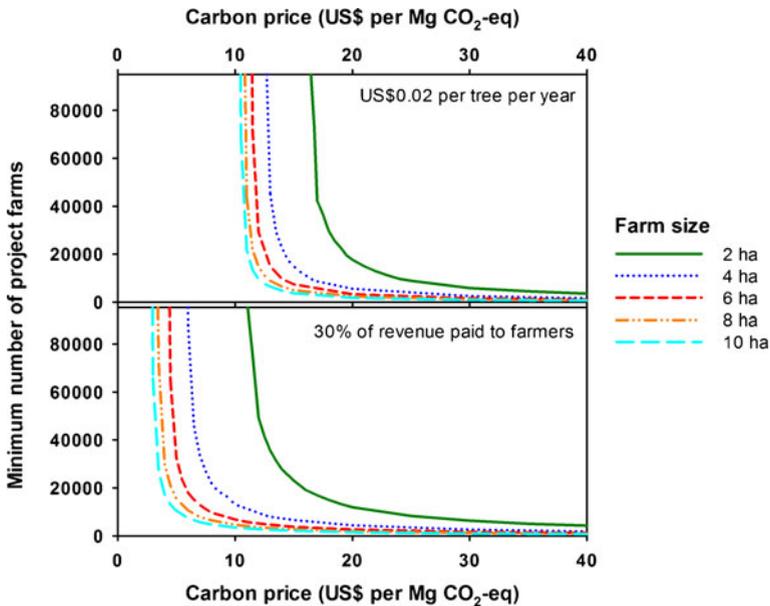
Fig. 2 Profitability thresholds for hypothetical TCPs in the Sahel, depending on the mean farm size, the number of farms, the carbon price and the payment scheme. For each farm size/payment scheme scenario, combinations of carbon price and number of farmers to the left of the lines signify that the project would incur a loss, whereas those to the right of the lines indicate profitable projects

prices above US$39.14 per Mg CO_2-eq (Fig. 4). It should be noted that all these calculations are based on a number of assumptions about the cost structure of TCPs in the Sahel (Table 1). Nevertheless, we believe that our results are indicative of the reality of carbon projects targeting Sahelian smallholders.

3.3 Climate analogues

All climate analogues of the Old Peanut Basin in Senegal were located close to the area's current location (Fig. 5, top). For the B2a emissions scenario, aridity and climatic suitability for parkland were similar to present conditions for most climate scenarios, with one scenario (HADCM3; 2080s) projecting strongly increasing aridity (Fig. 6, top left). For the A2a emissions scenario, increasing aridity was evident for two of the climate models (CCCMA and HADCM3). MaxEnt suitability scores were in line with aridity projections, with mostly stable conditions for the B2a scenario, and declining suitability for most projections under the A2a emissions scenario (Fig. 6, bottom left).

For Ségou and Zinder, analogue locations were spread over a longitudinal range of several thousand km, but with a small north–south extent (Fig. 5, middle and bottom), reflecting the latitudinal rainfall isohyets of the Sahel. For Ségou, the CCCMA model consistently projected decreasing aridity, while the other two models projected drier conditions (Fig. 6, top middle). Suitability of this location for parklands tended to decrease for all scenarios after the 2020s (Fig. 6, bottom middle). For nine out of 18 future scenarios, MaxEnt scores close to or below 0.2 for many of the 50 closest climate analogues suggest that conditions may deteriorate substantially in the future.
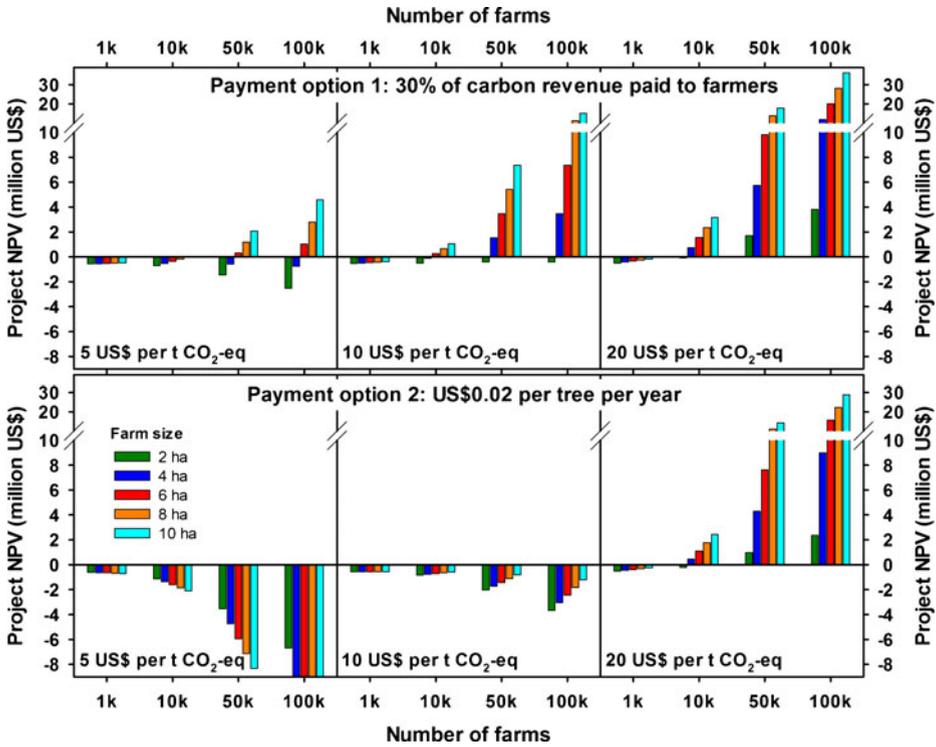
Fig. 3 Net Present Value (NPV) estimates of hypothetical Terrestrial Carbon Projects in the Sahel, depending on number of farms in the project, average farm size and payment scheme

For Zinder, projected rainfall changes were relatively small (Tab. ST2), but these had strong effects on aridity and MaxEnt suitability. For the 50 closest pixels to Zinder in the baseline scenario, aridity index values were low for all climate analogues (Fig. 6, top right). Suitability for parkland agroforestry was relatively low in the baseline, and fell below 0.2 in most future scenarios (Fig. 6, bottom right). Only in some analogue locations for 2020s

Fig. 4 Net Present Value (NPV) for farmers engaging in hypothetical Terrestrial Carbon Projects in the Sahel, depending on farm size, payment scheme and carbon price
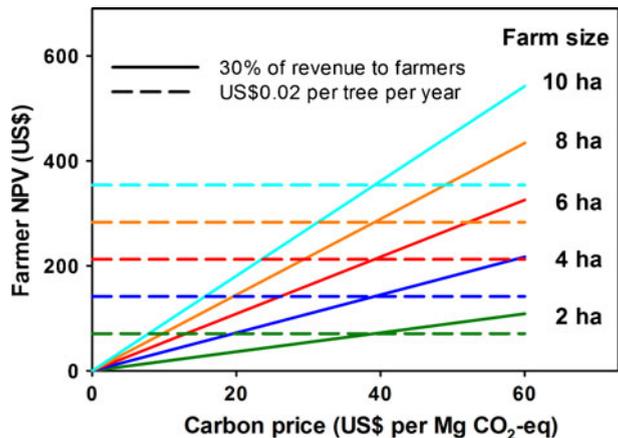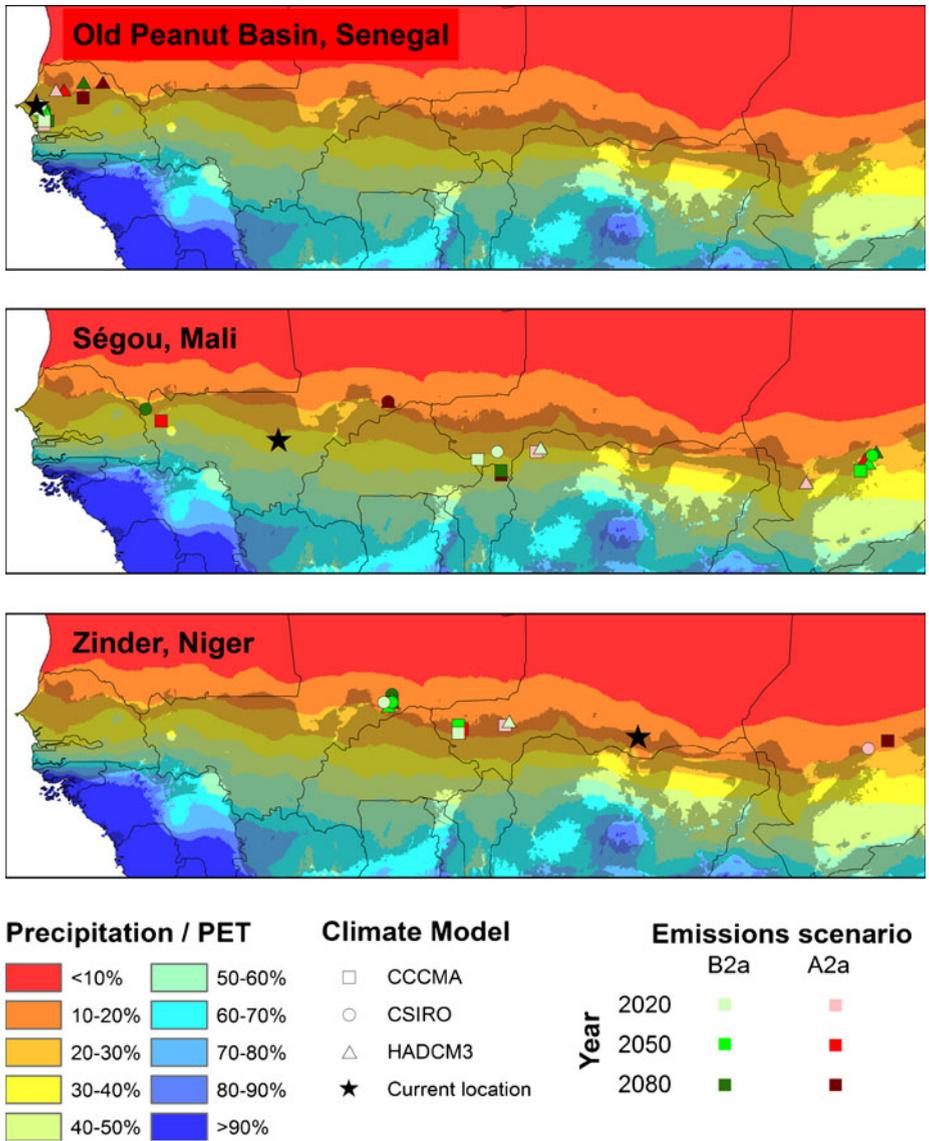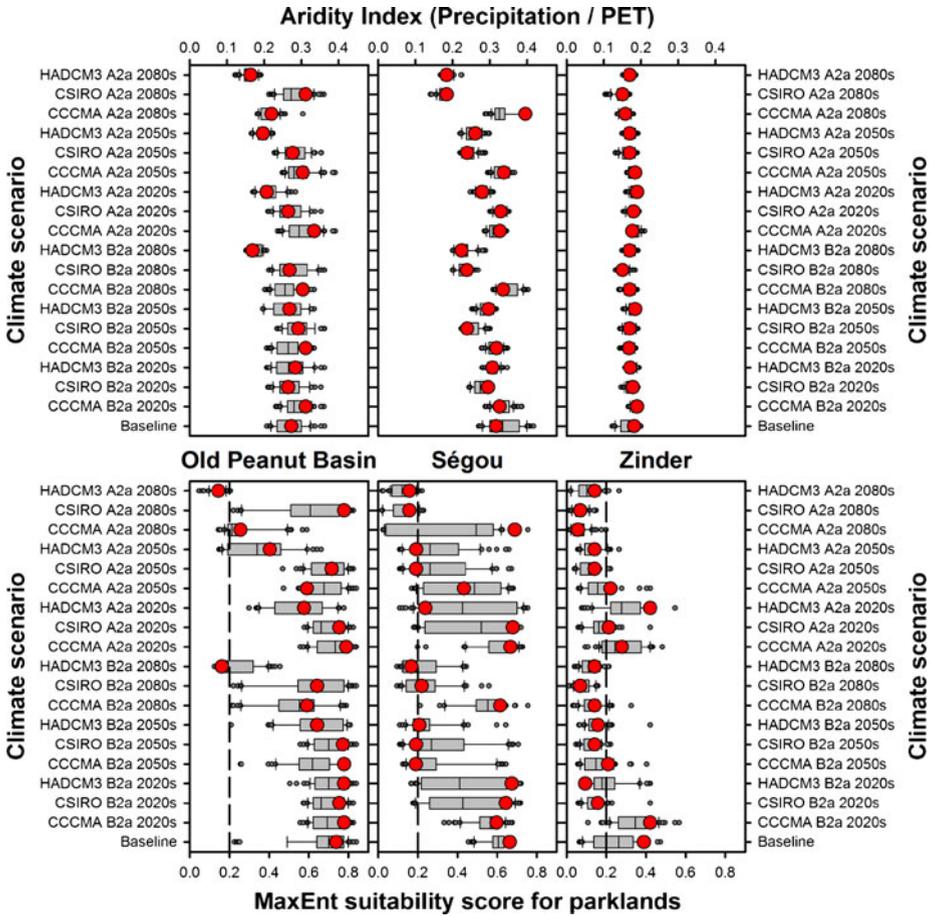
Fig. 5 Climate analogue locations for the Old Peanut Basin (Senegal, *top*), Ségou (Mali, *middle*) and Zinder (Niger, *bottom*) for 18 future climate projections. Climate analogues are the most similar locations in terms of current climate to climates projected for the target location in the future

scenarios did Zinder have suitability scores clearly above 0.2. With the exception of the CCCMA 2050s scenario, all analogue locations representing the 2050s or 2080s were unsuitable for parklands.

For all three locations, aridity index and MaxEnt scores depended strongly on the climate model used. This difference probably stems from differences between models in anticipating future changes to the annual shifts of the Intertropical Convergence Zone (Bellucci et al. 2010), which are crucial determinants of seasonal rainfall in the Sahel.

Fig. 6 Aridity Index values (*top*) and MaxEnt suitability scores for parkland agroforestry (*bottom*) for the current locations of the Old Peanut Basin, Ségou and Zinder (*baseline*), as well as for the best available modern day climate analogues of projected future conditions at the sites for 18 future climate projections. The *red dots* indicate conditions at the best analogue location, while the *box plots* show the distribution of index values among the 50 closest analogue sites

3.4 Future parkland areas and carbon stocks

Projected climatic changes substantially affected MaxEnt suitability scores, with the area classified as unsuitable (scores <0.2) increasing dramatically in some projections (Fig. 7). Suitable areas were projected to contract. The B2a emissions scenario projected a larger suitable area for parklands than the A2a scenario, corresponding to weaker greenhouse gas forcing in the B2a scenario (Table 3). For all future scenarios, potential carbon stocks in parklands were lower than in the baseline, ranging between 977 and 1,308 Tg C by the 2080s (Fig. SF3 of the Supplementary Materials). While these results should be considered with caution due to the range of underlying assumptions, they do indicate substantial uncertainty in the amount of carbon that can be stored in Sahelian parklands in a future affected by climate change.
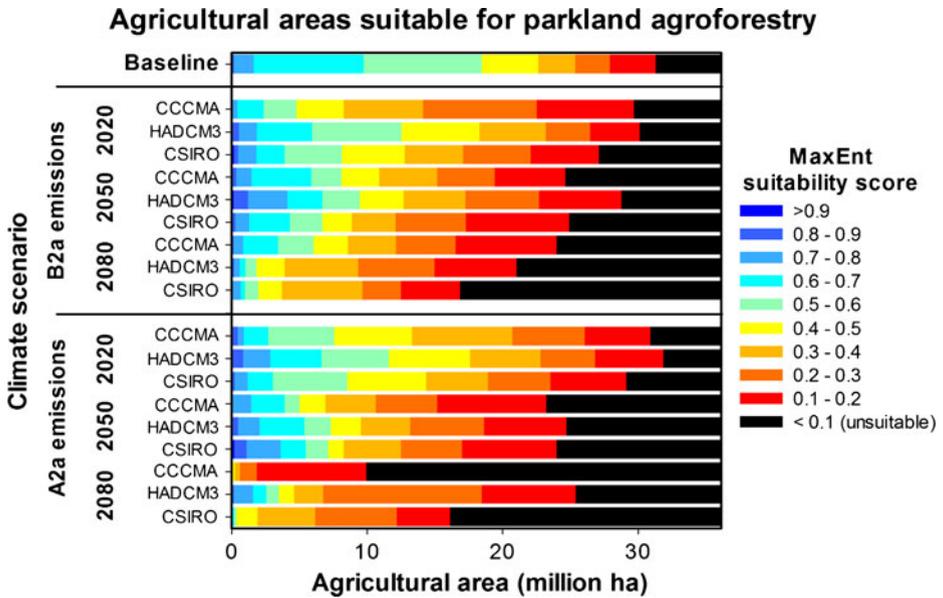
Fig. 7 Distributions of MaxEnt suitability scores across all Sahelian cropland for the baseline and 18 future climate scenarios

4 Discussion

4.1 Viability of terrestrial carbon projects

For the range of hypothetical TCP scenarios tested, only those with high carbon prices and/or the inclusion of large numbers of farmers were financially viable. These estimates rely on optimistic assumptions about rollout time, adherence to project requirements and tree survival rate. However, TCPs may increase profitability by reducing project costs, as evidenced by the success of TIST projects in East Africa (with P0.02 payment).

Given these assumptions, our results indicate that carbon projects would run at the margin of profitability, or even be unprofitable, at current carbon price levels. Recruiting the large number of farmers required for a TCP to be profitable may pose logistic difficulties. The geographical areas covered by a TCP would be large, because many farmers would be

Table 3 Agricultural areas in the Sahel classified as unsuitable, suitable and highly suitable for parkland agroforestry, according to MaxEnt ecological niche modeling. Results are shown for the Baseline and for each combination of emissions scenario and time period. For future projections, averages and standard deviation of three Global Climate Models are shown

Time period	Emissions scenario	Unsuitable (<0.2)	Suitable (0.2–0.5)	Highly suitable (>0.9)
		Million ha		
2020s	B2a	12.5±2.4	15.2±2.2	8.5±3.9
	A2a	10.7±1.7	16.2±1.9	9.2±2.1
2050s	B2a	16.3±2.7	11.7±1.4	8.1±1.4
	A2a	19.2±1.7	10.5±0.8	6.5±1.3
2080s	B2a	21.5±2.0	11.4±1.5	3.3±2.4
	A2a	25.3±8.4	9.5±6.9	1.3±1.9
Baseline	–	8.2	9.4	18.5

ineligible for a TCP or other Payment for Environmental Services scheme (Swallow et al. 2009; Wunder 2008) due to unclear or insecure tenure (Tschakert 2004; Woomer et al. 2004). Projects covering thousands of farmers across cultural groups and administrative boundaries would be difficult to manage. Managing a TCP of the required size would also imply high risks for the project developer. The high number of necessary participants, the long lag times between investment and break-even and the possibility that farmers can sell the trees they have planted within the project, among others, provide considerable risk that needs to be factored into the buffer and the insurance against default, both of which would raise project costs.

Probably the most limiting factor to the success of TCPs is their limited economic attractiveness for farmers. According to Tschakert (2004), annual farm household incomes in the Peanut Basin of Senegal ranged from \$577 to \$2,293 in 2001, and current per capita incomes are \$755, \$1,252 and \$1,819 for Niger, Mali and Senegal (World Economic Outlook database; http://www.imf.org). At a carbon price of US\$20 per Mg CO_2-eq, even for large farms and assuming the most beneficial payment scheme, farmer NPV would only be around US\$350. This means that the perceived revenue from a commitment over 25 years is substantially lower than the annual income of even the poorest group of farmers. For small (2-ha) farmers, with NPVs between US\$36 and US\$71 at US\$20 per Mg CO_2-eq, engagement in a TCP is even less attractive. For these farmers, NPVs were always lowest, making it unlikely that profit-oriented TCPs would target the poorest farmers. For such farmers, it is also likely that a discount rate of 12 % is unrealistic. From a study of small farmers in the Philippines, Lumley (1997) concluded that discount rates as high as 40–50 % are more appropriate for small, resource-constrained farmers. Raising the discount rate to 40 % reduced the NPV for 2-ha farms to negligible values between US\$0.54 and US\$6.44, under the P30% payment scheme, and to US\$28.00 for the P0.02 scheme. At a 50 % discount rate, NPVs were between US\$0.29 and US\$3.45 for the P30 % scheme and US\$24.00 for the P0.02 payment option. These findings mirror results from a recent study on carbon sequestration through agroforestry by smallholder farmers in Mexico, where the attractiveness of such activities for farmers was found to be highly sensitive to the discount rate (Balderas-Torres et al. 2010).

All these NPV estimates do not include costs for managing trees over 25 years or opportunity costs of other possible land uses. They may also be based on optimistic assumptions about transaction costs, which have been identified as the potentially greatest barrier to adoption of carbon sequestering activities by smallholder farmers (Lasco et al. 2010). Sovacool (2011) reported that in projects registered under the Clean Development Mechanism, typical transaction costs are about 5 % of the contract value, but for a project rewarding small farmers in Mexico for implementing agroforestry practices, Balderas-Torres et al. (2010) reported transaction costs of between 17 % and 24 % of the project value. Their study estimated that for farms averaging 13 ha, carbon prices between US\$5.3 and 11.5 per Mg CO_2-eq (US\$19.3–42.1 per Mg C) were required in order to break even, in projects involving up to 1,538 farmers. At comparable carbon prices, our hypothetical projects in the Sahel required about 20,000 farms with 6 or more ha to break even, indicating lower potential for smallholder carbon projects in the Sahel than in Mexico.

These considerations indicate that carbon sequestration in dryland areas using agroforestry practices is unattractive for smallholder farmers, if these activities are pursued solely to attract carbon payments. These findings cast doubts on the prospects of carbon payments to alleviate poverty among the poorest farmers in the Sahel, if carbon sequestration is the main focus.

Some recent studies have highlighted the potential of smallholder farmers to receive payments for other environmental services, such as biodiversity conservation, watershed

protection or landscape beauty (Milder et al. 2010). Where such payments can be bundled with carbon payments, returns to farmers may increase (Wendland et al. 2010). Bundling of ecosystem services has been shown to have potential in areas of high biodiversity (e.g. Madagascar; Wendland et al. 2010) or where potential areas for carbon sequestration also fulfill important watershed or recreational functions (e.g. Phillippines; Villamor and Lasco 2009). In the relatively scarcely populated drylands of the Sahel, however, it seems doubtful that significant payments for non-carbon ecosystem services could be generated. Biodiversity in these systems is relatively low compared to the humid tropics, and demand for local ecosystem services, such as watershed conservation or landscape beauty is unlikely to be high enough to generate cash flows to farmers, except potentially in the periphery of cities.

From the presented data and discussion, it is clear that carbon as a commodity is not sufficiently valuable to provide incentives for farmers in the Sahel to involve in TCPs. However, the suite of benefits that trees provide can be of much greater value. For instance, growing the fertilizer tree *Faidherbia albida* in the Sahel can increase crop yields by between 50 % and 170 % (Garrity et al. 2010). Erosion control, improved microclimates and improved water and nutrient efficiency can further contribute to overall landscape health. Tree products can also help diversify the number of marketable products or improve family health (e.g. through essential vitamins in fruits). This can provide financial assets or higher food security, reducing farmer vulnerability to climatic and other exogenous shocks. Additional marketable products, soil fertility or favorable microclimatic conditions can help adapt farmers to climate variability and climate change (Haglund et al. 2011). Hence, the carbon component of projects could potentially serve as a catalyst that allows farmers to invest in climate-smart practices such as agroforestry, particularly where up-front payments can be realized (Neufeldt et al. 2011).

Farmers elsewhere have adopted agroforestry practices for a wide range of reasons, including additional income from trees, soil conservation, production of construction materials, diversity of harvest and shelter from strong winds (Magcale-Macandog et al. 2006). In Maradi, Niger, recent farmer-managed regeneration of parkland systems seems to have been motivated primarily by the prospects of improved soil fertility, and the production of fuelwood and marketable tree products, resulting in additional income (Haglund et al. 2011). Haglund et al. (2011) estimated that the deliberate protection and management of naturally growing parkland trees has raised income levels by between US$26 and US$46 per capita and year. These estimates are much higher than potential incomes from carbon sales estimated in the present study. Non-carbon benefits thus appear to have a greater positive effect on farm profitability than payments for sequestering carbon.

4.2 Climate change impacts and adaptation

Rather than benefitting from opportunities provided by climate change, farmers in the Sahel may find themselves confronted with severely deteriorating climatic conditions. Our analysis indicated that parkland systems may experience increasingly unsuitable conditions, which may lead to range contractions. Trying to raise landscape level carbon stocks against this climatic trend may prove impossible. Maranz (2009) reported that many tree taxa in this environment are already in decline and that savannah parklands are senescing due to decreasing rainfall. Gijsbers et al. (1994) reported that seedlings of key tree species are no longer able to survive during the dry season. These observations may be symptoms of decreasing suitability for parklands.

Where parkland areas can be expanded, these may help farmers adapt to the impacts of climate change. Unlike rainfed annual crops, trees can draw water from deeper soil layers

and are thus able to produce food, fodder and fiber, even when annual crops fail. Fertilizer trees can provide much-needed resources that allow raising yield levels. Finally, trees on farms can help diversify incomes and thus buffer farmers against the economic shocks that may occur during years of unfavorable weather.

The climate trajectory for the Sahel is far from clear. With projections ranging from unchanged conditions to strongly increasing aridity, governments and farmers have no unequivocal basis for managing the transition. However, with many future scenarios indicating increasing aridity, it seems likely that inadequate efforts to adapt will make farmers increasingly vulnerable to the extremes of a rainfall distribution that is shifted towards drier conditions than prevail today. The cost of the necessary adaptation measures is likely to exceed the value of carbon that can be stored in Sahelian cropping systems. It appears that in the Sahel, the opportunities provided by climate change will be greatly outweighed by the challenges it presents.

5 Conclusions

Carbon stocks in Sahelian parklands are substantially higher than in croplands in this region, but deterioration of climatic conditions may reduce suitable ranges for this agroecosystem. Substantial climate risks are thus incurred in the establishment of parklands for carbon sequestration, especially if carbon sales are needed to make such efforts economically viable. Even if climatic conditions remain unchanged, economically viable Terrestrial Carbon Projects (TCPs) require large numbers of farmers and carbon prices that are higher than at present. Economics on the farmers' side made carbon sequestration seem like an economically unattractive option. Nevertheless, the recent re-establishment of thousands of hectares of parklands in Southern Niger, without any payments for carbon sequestration, indicates that non-carbon benefits may very well be a motivating factor leading to large-scale establishment of parklands.

Providing benefits from TCPs to the poorest farmers will be challenging, because such farmers are the least profitable ones for investors to work with. Net Present Values for small farmers were low, especially when considering the high discount rate on future revenue that they likely apply. The unpredictability of the ecological and economic framework for carbon projects in the Sahel, with uncertainty about future climate and the survival of trees, as well as future carbon prices, make this region a high-risk area for profit-oriented investments in TCPs.

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