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Reforestation and sylvopastoral systems in Sahelian drylands: evaluating return on investment from provisioning ecosystem services, Senegal

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Since the 1960s, droughts have caused significant degradation of Sahelian ecosystems, particularly resulting in a reduction in tree cover. Despite the challenges posed by climate change, the rural Sahelian population continues to depend on natural resources for pastoral livestock farming, which remains a critical source of livelihood. To address this issue of land degradation, Sahelian states and international coalitions are prioritizing efforts to restore pastoral land through reforestation programs. These initiatives aim to enhance ecosystem services, generate new income for the population, and safeguard biodiversity.In practice, however, reforestation has often led to a depletion of resources for communities due to enclosure policies. This paper explores various land management models for reforestation within a pastoral context through provisioning ecosystem services (PES) modeling.This study quantifies the economic potential of PES offered by reforestation programs in Senegal. It employs a quantitative methodology to assess the profitability of these operations from the perspective of pastoral economies. The analysis reveals that the PES benefits of reforestation can significantly enhance the economic potential of sylvo-pastoral productions if resource access is negotiated collaboratively between pastoralists and forestry extension services during reforestation activities and after. From an investment perspective, the economic viability of reforestation operations in drylands is questionable. The findings suggest that when evaluated solely in terms of PES profitability, these programs may not be financially sustainable. The sustainability of these investments would require taking into account supporting and regulating ecosystem services.

KEYWORDS

reforestation, pastoralism, sustainable land management, cost-benefit, Sahel

1 Introduction

In a succession of droughts from the 1960s through the 1990s, Sahelian ecosystems suffered significant degradation, particularly in the loss of tree cover (Mbow et al., 2015). This transformation to more open grasslands has been confirmed through the analysis of aerial imagery and the use of remote sensing at local scales (Dendoncker et al., 2020). The reduction in tree cover has led to a reduction in Provisioning Ecosystem Services (PES) provided to the population and biodiversity. The loss of ES is even more important because of the region's rapidly growing population. Moreover, this rural population continues to depend on the region's natural resources to ensure its livelihood through pastoral livestock farming (OECD/SWAC, 2014). In a context of scarcity, the use of natural resources by agriculture and livestock farming, leads to further land degradation and limits the capacity of natural environments to regenerate resources (Tappan et al., 2016).

Notwithstanding the context of increasing conflict, Sahelian states and international coalitions are focusing their efforts on restoring degraded land through programs such as the African Forest Landscape Restoration (AFR 100) initiative and the Great Green Wall (GGW) (Messinger and Winterbottom, 2016). These land restoration programs include eleven countries and involve reforestation of steppes and savannahs for the benefit of local populations and biodiversity. After 15 years of existence, the GGW is showing the first results that allow a mid-term evaluation. The GGW Accelerator, initiated in 2021, aims to scale up these restoration operations to 100 million hectares with the objective of enhancing the economic benefits for civil society organizations (CSOs) (Sacande et al., 2022a). It is therefore timely to reflect on the economic viability of restoration practices for agro-pastoral populations living in rural areas of the Sahel (Mirzabaev et al., 2022; O'Byrne et al., 2022; Sacande et al., 2021; Turner et al., 2021).

In the context of sustainable land management, restoration options focus on reforestation with the objectives of job creation, carbon sequestration, and biodiversity promotion, however, results on the ground show a limited success rate that is linked to low survival rates of the planted trees (Goffner et al., 2019; Delay et al., 2022). Reforestation activities often involve fencing off the area to limit the impact of young trees being trampled by roaming herds, but since rural Sahelian populations depend heavily on pastoralism to sustain their livelihoods, this fencing can create tensions and even conflicts with local populations who are supposed to benefit from the programs (Taïbi, 2019). In these areas, land ownership is predominantly governed by a combination of traditional rules and communal land tenure under strong state influence, leaving relatively few private landholders with access to private pasture or agricultural land. The management of land involves both state and community entities, which sometimes harbor conflicting objectives (Delay et al., 2022).

A global economic estimate suggests that, in many countries, the return on investment is negative. Overall, the balance sheet at the Sahel level is neutral with a gain of $1.2 USD for $1 USD invested (Mirzabaev et al., 2022). The socio-economic effect of this reforestation on the communities also seems weak despite the clear intention of these actions to benefit the most vulnerable populations (Turner et al., 2021).

This study was aimed at refining this global analysis through local modeling of pastoral land reforestation in the Sahel in order to better inform the debates on the sustainability of those restoration efforts. Our case study was conducted in the sylvopastoral zone of Senegal, one of the GGW participants. Our approach is based on a literature review and field surveys taken in 2021 and 2022, among herders and technical services, to characterize the agro-pastoral uses of the resource in question and to quantify the potential economic gain obtained through restoration efforts (Harrison et al., 2014).

Our results show the current difficulty of finding a viable economic model for reforestation of pastoral lands when land is set aside while only considering the economic aspects of the PES. In order to reach an optimal potential, it would seem necessary to better integrate pastoralism into reforestation operations and develop economic channels that would help local populations to manage and valorize their natural resources. Nevertheless, if the objectives are achieved, there would be a significant gain in terms of biomass available for the food system, which, in a context of population growth, is not negligible. Consideration of regulatory services could make operations theoretically profitable, but this also implies adapting the principles and protocols currently in use in reforestation.

2 Pastoralism and land restoration in the Sahel

2.1 Reforestation and pastoralism in the Sahel: from common objectives to land use conflicts

2.1.1 Degradation of pastoral land in the Sahel zone

The degradation of land and natural resources in the Sahel has received particular attention since the region's decolonization. The droughts of the 1960s–1990s had a significant effect on the productivity of agro-pastoral land and tree cover (Touré et al., 2012), and the evolution of land use shows decreases in tree and shrub cover through both climatic and anthropic effects. These changes can be partly explained by rainfall variation and the expansion of agricultural areas (Tappan et al., 2016). As rainfall decreases and population increases, pastoral systems face significant challenges from limited water resources and competition with agriculture for land use, resulting in overgrazing and land degradation during prolonged droughts. The growing population intensifies the demand for food and livestock products, further pressuring pastoral lands with agricultural expansion.

The measure of degradation varies depending on the time step considered. Analyses comparing landscapes before and after droughts reveal degradation over the long term, mainly in the 1970s and 1980s (Mbow et al., 2015). Analyses focusing on a more contemporary period show a stabilization of vegetation cover linked to an improvement in rainfall, all other things being equal in terms of the expansion of agriculture. However, the relative greening of the Sahel, observed since the beginning of the 21st century, should not obscure the fact that the population is growing rapidly, and as a result, the natural resources available per inhabitant are decreasing.

In addition, the Sahel is subject to high inter-annual and spatial variability of rainfall and its effect on the evolution of land productivity. Some regions have managed to maintain their level of productivity while others have seen their environment continue to deteriorate under the pressures of climate change. This is particularly the case in Mauritania and Senegal. In 2001 and 2015, the United Nations Convention to

Combat Desertification (UNCCD) estimated that half of the land in the Sahel was experiencing a downward trend in productivity, particularly in semi-arid agro-pastoral areas (UNCCD, 2022). On the ground, actors point out that degradation goes far beyond biomass productivity. It also takes the form of a decrease in tree and herbaceous plant diversity, wind erosion, and the appearance of invasive plants that are not palatable to grazing animals (Rahimi et al., 2021).

2.1.2 The socio-economic role of trees in the pastoral system

The role of pastoralism in land degradation is hotly debated. This livestock practice obviously makes it possible to produce goods and services with a low level of input by making use of natural resources such as pastureland. Low production costs make meat and milk accessible to a population largely living below the poverty line (Duteurtre and Faye, 2009). Pastoralism supports family farming in an arid and semi-arid environment. Mobility in a collective space allows herders to adapt their practices to an extreme environment in perpetual imbalance. However, sectoral policies promoting unregulated herd growth have led to a profound change in the relationship between herders and their environment. The carrying capacity of Sahelian pastures varies between 0.2 and 0.6 livestock units per hectare (LU/ha) (Assouma, 2016). The tropical livestock unit corresponds to 250 kg of live weight and is used to measure the weight of the various species of livestock (Wilson, 1981). In the absence of official statistics, it is difficult to know precisely the number of livestock in Sahelian pastoral areas, but some studies have estimated that the livestock kept far exceeds the local carrying capacities, forcing transhumance to pastures further south.

The “overstocking” of animals in Sahelian rangelands does not necessarily have a visible impact on the herbaceous and woody stratum in the medium and long term (Rahimi et al., 2021). In fact, the number of trees in the Sahel is increasing slightly in pastoral areas, although researchers note a scarcity of young trees among the woody population (Dendoncker et al., 2020). On the other hand, overgrazing can lead to a change in the composition of the herbaceous layer. In the short term, overstocking implies a more rapid depletion of biomass and thus triggers early transhumance, all things being equal in terms of the inter-annual variability of pasture productivity.

Trees are an essential resource for pastoral livestock to survive the dry season. Tree leaves represent up to 17% of the biomass ingested by cattle in the year, 40% by sheep and up to 70% by goats (Assouma, 2016). Therefore it is in the interest of livestock farmers to use this resource sustainably, especially since it also supports economic diversification within pastoral households.

2.1.3 The socio-economic stratification of the pastoral world and its use of trees

The use value of tree products depends on the socio-economic stratification of households in the pastoral system (Bakhoum et al., 2020). Woody and non-woody forest products are often exploited by the more vulnerable, young or women herders. Tree felling and gathering are usually undertaken by households with lower animal capital. A household with a large base of animal capital will value the tree indirectly for animal feed. During the dry season, the animals eat the leaves and fruit that are available. During the lean season, hired herders prune the trees to give the animals green branches with the remaining leaves. A survey in Senegal found that collecting non-timber forest products (NTFPs) accounted for almost half of the income of poor households and a quarter of household income in low-income households. Households with high livestock incomes derive almost no income from the marketing of NTFPs. The collection of NTFPs remains a profound social marker (O’Byrne et al., 2022).

The collection of NTFPs is part of an economic diversification for vulnerable households (Turner et al., 2021). In Senegal’s rural markets, *Balanites aegyptiaca* fruit is sold for between $0.34 and $0.68 USD/kg depending on the time of year, while gum arabic is sold for around $0.86 USD/kg. The fruits of baobab and jujube trees, although rarer in pastoral areas, are also sold. It is also possible to sell certain tree seeds used in animal feed (e.g., *F aidherbia albida*, *Acacia tortilis*, *Acacia seyal*). There are many opportunities to add value to tree and shrub products with transformation, such as *Balatnites* oil, *Boscia senegalensis* green peas, or *Calotropis procera* construction woods (Bakhoum et al., 2020; Delay et al., 2022).

In Sengal, however, the exploitation of NTFPs is subject to authorization by the Water and Forestry Service. This harvesting and marketing authorization costs from $1.72 USD per week to $3.44 USD per month, and is difficult to obtain. Its cost represents a quarter or even half of the collectors’ income (survey, Niassanté, Sénégal, March 2021); but the authorization itself does not distinguish between pickers and traders. The exploitation of NTFPs is often illegal and subject to strong tensions between the Water and Forestry Service and the local populations (Blundo, 2014; Jones Sánchez, 2020).

The most important tension related to the trees lies in the increasing need for wood energy, especially firewood. Access to energy in these regions remains highly dependent on the renewal of natural resources. Installation of solar energy production and biogas from manure are rare, and rapidly increasing urban demand leads to a lucrative illegal trade and significant plundering of wood resources from pastoral lands. The carbonization and removal of dead wood is part of a high-yield illegal economy with logistical chains organized by wealthy sponsors. This timber trade is particularly difficult to control because the economic stakes are high (Peltier, 2019).

2.1.4 The great green wall reforestation protocols in Senegal

Faced with the reduction in tree cover, Sahelian states have committed to reforestation policies. The Great Green Wall is the iconic reforestation project in the region, encompassing a swath of the Sahel 7,000 km long and 15 km wide (Dia and Duponnois, 2012).

In Senegal, operations are concentrated in reforestation plots established in 2007 and 2008. The agency has a band of fifty plots assembling a total surface area of about 30,000 ha (PAGGW, 2021)[1]. The band is mainly located in the sylvo-pastoral zone composed of reserves and classified forests where the Fulani population makes a living with livestock and the more or less legal exploitation of timber and non-timber forest products.

Most of the Senegalese reforestation plots have been fenced off to limit the roaming of domestic animals. The plots range in size from a thousand hectares for the largest to less than a hundred hectares for the smallest. Reforestation is carried out sequentially with a mixture of species composed mainly of *Acacia senegalensis,*

1 Source: https://www.grandemurailleverte.org/ (accessed 10/10/2022).

A. tortilis, *A. seyal* and *Balanites aegyptiaca* (Wade et al., 2018). The seedling density is about 156 trees/hectare, which is ten times the density observed outside the reforestation plots. After 15 years of activity, the results are poor. The survival rate of seedlings is less than 30%. Only a few hundred hectares have exceeded 75 trees/ha and a large proportion of the plots are no longer fenced because of budgetary limits and sabotage resulting from local tensions with livestock farmers. The official budget for operations is $600 USD/ha (PAGGW, 2021).

The creation of the Great Green Wall Accelerator in 2021 raises the question of the value of scaling up the reforestation protocol and covering 11 countries (Dia and Duponnois, 2012; Mirzabaev et al., 2022; O'Byrne et al., 2022; Turner et al., 2021). To reduce tensions with the affected populations, more recent reforestation protocols have encouraged greater participation of the population in the operations through the creation of economic interest groups (EIGs), plot managers, and women's organiszations to valorize NTFPs. The EIGs work to find economic value for bush straw that was previously left in the plots and supervise harvesting within the plots (Sacande and Parfondry, 2018). The results of the newer protocols show a degree of appeasement even if the land issues remain tense. The question of the duration of fencing raises the question of the time horizon of the restoration. Is it a temporary, collective privatization of land? Or, is it a definitive transformation in the status of pastoral land? In the case of land tenure transformation, the reforestation objectives might be impossible to achieve because they contribute to a progressive scarcity of land. In the case of temporary collective privatization, it is important to consider the duration of the enclosure and how EIGs evolve after reforestation work is completed. Taking a forward-looking approach to evaluating the social and economic aspects of the Great Green Wall operations could help solve potential problems (O'Byrne et al., 2022).

3 Method

3.1 Giving value to restoration: elements of a potential physical economy

As part of its action to combat desertification, the FAO published a report entitled, "Non-timber forest products, from restoration to income generation" (Sacande and Parfondry, 2018). The authors stress the importance of restoring natural products in creating income and employment through examples such as the valorization of straw, arabic gum, and balanites oil. This information is well known to the development stakeholders, but there is still a question of how much can be gained by restoring degraded land. Since the creation of the Accelerator, a number of socio-economic evaluations of restoration have been published (Mirzabaev et al., 2022; O'Byrne et al., 2022; Sacande et al., 2021; Turner et al., 2021). According to the estimate of Mirzabaev et al. (2022) the rate of return on investment in reforestation in the semi-arid zone would be $1.39 USD per dollar invested, notwithstanding the strong heterogeneity between countries. Reforestation operations in the Sahel would have an average financial cost of $650 USD/ha for the first year of installation and $250 USD/ha for follow-up over 30 years. According to this study, the benefits from reforestation are $2151 USD/ha over 30 years with 13% of the benefits realized from the PES ($284 USD) and the remaining 87% from the regulation of ecosystem services ($1838 USD). The benefit of providing additional ecosystem services seems to be low. It would therefore be interesting to detail the calculations here in a specific case, namely, the sylvopastoral zone in Senegal.

3.2 Modeling the benefits of provisioning ecosystem services in pastoral areas

In evaluating ecosystem services, the choice of profitability as a variable in the conceptual framework is justified by its significance in understanding the economic value of these services to society. Profitability measures the net gain or benefit obtained from an investment or activity, and when applied to ecosystem services, it helps quantify the economic benefits that ecosystems provide to humans. The conceptual framework draws from the work of Mulder et al. (2015) and the Millennium Ecosystem Assessment (MEA), both of which emphasize the importance of incorporating economic valuation in ecosystem service assessments. By considering profitability, we can assess the economic viability and potential returns on investments in ecosystem conservation and restoration projects. This is especially relevant in the context of the Great Green Wall initiative, where resources are allocated to reforestation efforts and sustainable land management practices. Profitability analysis allows decision-makers to compare the costs of ecosystem restoration or conservation with the monetary value of the PES by these ecosystems. It helps decision-makers prioritize interventions that yield the highest returns on investment and maximize the benefits to local communities and the broader society. However, it is essential to recognize that the concept of profitability should not be viewed in isolation but as part of a comprehensive framework that also accounts for other critical variables. The framework should also encompass qualitative and non-monetary dimensions of ecosystem services, such as biodiversity conservation, cultural significance, and resilience to climate change. Including these aspects ensures a more holistic understanding.

In this article we are particularly interested in the PES because these products have an economic local market value (Figure 1). We do not take into account regulatory, support, or cultural ecosystem services because their economic values are more dependent on the international market (Groot et al., 2012).

The various prices and values used in the modeling are derived from direct observations in the Ferlo region of Senegal between March 2021 and May 2022. These observations and discussions have been supplemented with technical parameters from the literature or confirmed through research articles. Wood, fruit, and straw are traded on local market and therefore have a price (Bakhoum et al., 2020). At the same time, a significant part of the quantities collected is self-consumed. It is therefore possible to attribute a substitute value to them (Wane et al., 2020). To engage local people in restoration operations, it is important that the PES can at least offset the costs of restoration.

Among the PES considered in this paper, we focus on food, animal feed, and wood energy. Traditional medicine,

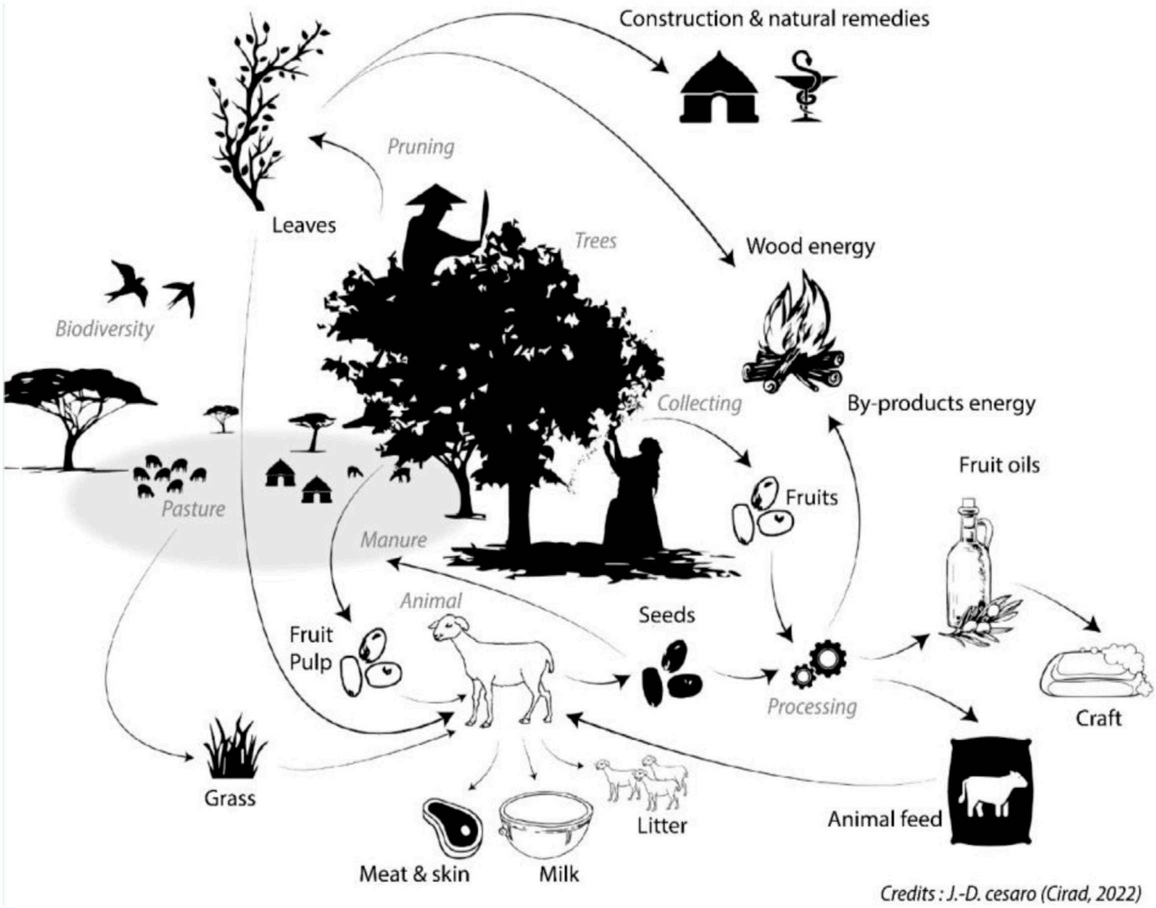

FIGURE 1
Pastoral uses of natural resources across all seasons: overview of Provisioning Ecosystem Services in the Sahelian region.

cosmetics, handicrafts, or construction products are not included because of the complexity related to the specificity of their use.

In assessing the restoration potential, we consider the following values:

3.2.1 Grazing

For pastures, we consider the average biomass productivity of one tonne per hectare taking into account interannual variability ranging from 0.5 to 2.5 tonnes of dry matter (DM) per hectare. The dry matter content is around 90%, of which 30% is consumed by domestic animals. The rest (70%) goes to the ecosystem through Sun exposure, wind, livestock trampling, wildlife feeding, and seedling (Assouma, 2016).

The value of a kilogram of straw is calculated while taking into account the output of the animals and the final market value of the animal. For example, the price of a 9 year old cow is about $510 USD (Sow et al., 2021). In its lifecycle, a cow will have 4 calves worth $85 USD per calf. The initial value of the cow as a calf ($85 USD) must be subtracted, so the total value of calving is estimated at $255 USD. The cow will produce 200 L of milk for human consumption at $0.4 USD per liter (Corniaux et al., 2012). The total value of milk is estimated at $320 USD. The total value of a cow is estimated $1085 USD. The grass consumption of a cow over 1 year is 1,350 kgDM, which is 12,150 kgDM for 9 years. This gives a value of $**0.09 USD/kgDM.**

In order to further refine this calculation, it would be necessary to take into account the rate of males in the herd, the weight of the animals for sale, and the marketing strategies for the animals. It would also be necessary to consider the populations of small ruminants, since cattle only represent 70% of the total livestock units in Senegal. For this first estimate, we therefore consider the average value of grass used by cows. The average value of grass per hectare/year in a pasture is therefore 1,000 kgDM x 30% x $0,09 which is **$27 USD/ha/year.**

3.2.2 Harvested grass

For the value of the straw harvested in the Great Green Wall plots, the entry price is $1.7 USD/cart (interview with water and forestry agents, Tessékéré, Sénégal, May 2022). The weight of straw that a cart can take is estimated at 200 kgDM. The harvested grass has a price valuation of $0.0085 (survey observation, Tessékéré, Sénégal, May 2022)[2]. This grass is used to feed animals, especially during the dry season. We therefore deduct $0.0085 from the $0.09 USD/kgDM value of the grass. There was no estimate of the quantity of grass per hectare in a

2 Cassecs Survey.

reforestation plot. We consider that the combined effect of Sun, wind, wildlife feeding, and seedling depreciates the yield by 50% in a reforestation plot (Assouma, 2016). The purchase price of grass is set at 1,000 kgDM x 50% x $0.0815 USD which is **$40.75 USD/ha/year.**

3.2.3 Resources from the trees

For trees, we consider an initial situation of 15 mature trees/ha with a canopy greater than 3 m^2, knowing that there is a large spatial variability between the tops of the dunes (0–10 trees/ha), the plains (10–30 trees/ha) and the lowlands (more than 30 trees/ha) (Dao, 1993; Dendoncker et al., 2020).

For the landscape trees' species composition—which has an influence on fruit diversity and aerial forage productivity—we simplify the composition observed to three types: *Balanites aegyptiaca* (77%), *Acacia senegal* (14%), and *Acacia tortilis raddiana* (8%) (Diouf et al., 2005; Ngom et al., 2013; Ousmane et al., 2013; Ndong et al., 2015).

3.2.4 Aerial leaf biomass

For the use of above-ground biomass, we estimate the quantity of leaves and fine branches that can be ingested by the animals. It is necessary to estimate the quantities that can be recovered directly by the animals and the quantities from various pruning practices carried out by farmers. Tree pruning is a common pratice in the dry season to feed animals with leaves from the cut branches. Those practices are also questioned as an unsustainable level of exploitation of this above-ground biomass.

According to Barral et al. (1983), tree leaf production in the Sahel is estimated at 30–40 kgDM/year per tree, and 50% of that is consumed by animals, either directly or harvested and given as feed. Other estimates suggest a leaf production of 7 kgDM per tree (Hiernaux et al., 2023). We will use the latter estimate. Indeed, the leaves of *B. aegyptiacaand and A. Senegal* are consumed during the lean season when grass is scarce. We therefore consider that they are a substitute for industrial supplements whose 1 feed unit (FU) value has been set at $0.25 USD/kgFU (interviews with feed retailers, Richard-Toll, Sénégal, may 2022), while the leaves have a value of 0.67 FU (Barral et al., 1983).

- Without pruning, animals are able to consume 10% of a tree's leaves. We obtain a value for the leaves and young shoots: 15 trees*7 kgDM*10%*0.67FU*$0.25 USD/kgFU = **$1.8 USD/ha/year.**
- With pruning animals can consume up to 50% of the tree's leaves: 15 trees*7 kgDM*50%*0.67FU*$0.25 USD/kgFU = **$8.8 USD/ha/year.**

3.3 The fruits of the trees

3.3.1 *B.* aegyptiaca: fruit, oil, wood

Fruit production per tree is estimated at between 2 kgDM/year per tree (Ouédraogo et al., 2022) and 4 kgDM/year per tree (Dao, 1993). We consider a value of 3 kgDM/year for harvesting and 2 kgDM for animal feed. In fact, there are two possible outcomes. Domestic (or wild) animals consume the fruit and eat mainly the rind and pulp, or the fruit is picked by humans for self-consumption, processing, or marketing. In the first case, we consider that 100% of the fruit can be consumed by animals. In the second case, we consider that the harvest cannot exceed 50% of the production because part of the fruit will have already fallen at harvest time. What is not picked by humans is consumed by animals.

The price of the fruit is about $0.25 USD/kgDM, which means a potential fruit harvest of 15 trees/ha*70% Balanites*50% harvest*3 kgDM*$0.25 USD = **$4 USD/ha/year of marketable fruit.**

The value of the pulp consumed by the animals must be added (i.e. 25% of the KgDM). The value of the pulp is 1.13 FU (Boudet and Rivière, 1968) and the value of the FU is about $0.25 USD/FU. We therefore have 15 trees/ha*70% Balanites*50% unharvested fruit*2 kgDM*25% pulp*1.13FU*$0.25 USD/FU which is **$0.75 USD/ha/year.**

If there is no harvesting, then all the fruit is consumed: 15 trees/ha*70% Balanites*100% unharvested fruit*2 kgDM*25% pulp*1.13FU*$0.25 USD/FU which is **$1.5 USD/ha/year.**

If farmers process the fruit of *B. aegyptiaca* into oil, they collect the pits directly from the pens of the small ruminants. We assume that 50% of the quantity of fruit ingested by the animals ends up in the night pen. In the case of harvesting activity, 25% of the kernels from the trees will end up in the pen. In the case of no picking activity, 50% of the pits will remain in the livestock warden. To make oil, the kernel (25% of the KgDM of fruit) must then be separated from the shell (50% of the KgDM of fruit). The yield of oil from the kernel is 45%. (Boukar, 2014). The price of oil is around $3.4 USD/L (local market price, Tessékéré, May 2022).

- In the case of harvesting, the oil value per hectare would be 15 trees/ha*70% Balanites*2 kgDM weight fruit*25% fruit*25% kernel*45% oil*$3.4 USD/L = **$2 USD/ha/year.**
- In the case of no harvesting, the oil value per hectare would be 15 trees/ha*70% Balanites**2 kgDM*50% fruit*25% kernel*45% oil*$3.4 USD/L = **$4 USD/ha/year.**

The co-product of oil extraction is the cake of the kernel (55% of the kernel). Its FU value has not been published. We consider an average value of 1.1 FU/kgDM.

- In the case of harvesting, the value of the cake would be 15 trees/ha*70% Balanites*2 kgDM*25% fruit *25% almonds*55% cake*1.1FU*$0.25 USD/FU or **$0.2 USD/ha/year.**
- In the case of no harvesting, the value of the cake would be 15 trees/ha*70% Balanites**2 kgDM*50% kernels*25% almonds*55%cake*1.1FU*$0.25 USD/FU or **$0.4 USD/ha/year.**

The weight of the hull is 50% of the weight of the fruit. The price of a kilo of hull used for energy is about $0.05 USD/kg (market price of low quality wood, Tessekere, May 2022).

- In the case of harvesting, the value of the hull would be 15 trees/ha*70% of B. *aegyptiaca**2kgDM**25% fruit *50% of hull*$0.05 USD/kg or **$0.13 USD/ha/year.**

- In the case of no harvesting, the value of the hull would be 15 trees/ha*70% B. *aegyptiaca* **2 kgDM*50% fruit*50% hull*$0.05 USD/kg or **$0.27 USD/ha/year.**

3.3.2 *A. senegal*: gum and seeds

Arabic gum production is about 0.25 kg per tree/year (Diallo et al., 2011). The price of gum is 1.7$/kg in pastoral areas (Tessékéré market price, May 2022). 15 trees/ha*14% of A. *senegal**0.25 kg of gum * 1.7$/kg or **$0.89 USD/ha/year**.

Pod production is about 2–3 kg per tree. The market value of the pods sold for animal feed is $1.72 USD per 7 kg bag (Niassanté market price, April 2022), which is a value of $0.16 USD/kg. The total for pods is 15 trees/ha*14% of *A. senegal**2.5 kg of pods * $0.16 USD/kg or **$1.26 USD/ha/year.**

3.3.3 *A. tortilis raddiana*: gum and seeds

The gum and seeds of A. *tortilis* are used in medicine or animal feed. The market price is $1.72 USD per 7 kg bag (Niassanté market price, April 2022), which represents a value of $0.16 USD/kg. One tree produces an average of 5.5 kg (Menwyelet, Coppock, and Detling, 1994); 15 trees/ha*8% of A. *tortilis**5.5 kg of pods * 142 XOF/kg **or $1.6 USD/ha/year.**

3.3.4 The wood of trees

There is a lack of data on the productivity of wooded pastures in semi-arid zones. Very often the studies concern fallows in the Sahelo-Sudanian zone. But studies on wood productivity indicate a growth of 0,12 m^3/ha/year with a ratio of 800 kg per m^3 (Nouvellet et al., 2003), which is 96 kg/ha/year for 15 trees/ha. The wood is sold on the markets at a price of about $0.09 USD/kg (market price, Tessékéré, May 2022), which represents a value of $**8.64 USD/ha/year.**

We do not know the impact of tree density on wood productivity during reforestation or on the capacity for natural renewal. In our model, we consider a linear process of productivity and a natural renewal of the resource at the level of cubic meters of growth for 15 trees/ha. We therefore consider that any wood above 0.12 m^3/ha is a non-renewable resource taken from the plantations. In other words, our model takes into account the destocking of wood (for self-consumption or sale) from the plantation during the life cycle of a reforestation plot opened after 7 years (Kairé, 1999) (Figure 2).

The values of the various PES that were considered are shown in Table 1.

3.4 Modeling the return on reforestation investments according to reforestation protocols

This assessment from the literature and the collection of market prices in the sylvopastoral area between 2021 and 2022 can be combined under different land use scenarios.

- S1: Low valuation:
  - valorization of herbaceous fodder
  - woody fodder valorization—low (without human intervention)
  - indirect use of pulp by animals (100% of total)
- S2: Low-medium valuation:
  - valorization of herbaceous fodder
  - woody fodder valorization—high (with human intervention)
  - indirect use of pulp by animals (100% of total)
  - wood valorization
- S3: Medium-high valuation:
  - valorization of herbaceous fodder
  - woody fodder valorization—high (with human intervention)
  - fruit picking and selling (30% of total fruit)

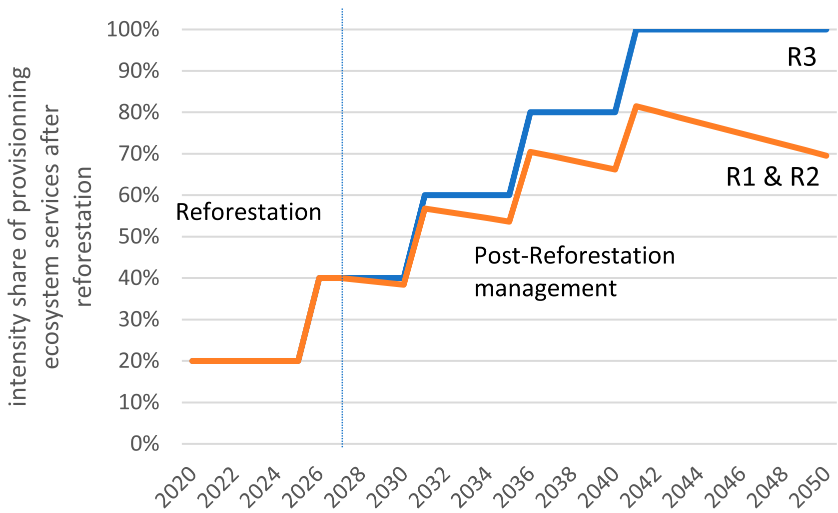

FIGURE 2
Impact of wood resource extraction on the intensity share of ecosystem services (R1, R2) versus no extraction in R3.

TABLE 1 Quantification of PES services in a pasture with 15 trees/ha.

Usage resources	USD/ha/year	Management scenario	Restoration scenario	Method of choice
Herbaceous consumed by animals	27	S1, S2, S3, S4	R0, after R1 & R2	Choice of manage the straw
Herbaceous collected by humans	40.75	S1, S2, S3, S4,	R2, R3	
Leaf consumed by animals without pruning	1,8	S1	R0, after R1 & R2	Choice of pruning
Leaf consumed by animals with pruning	8.8	S2, S3, S4, Not allowed in restoration period	R0, after R1 & R2	
Total value of *balanites aegyptiaca* fruit with picking and processing	7,21	S3, S4	R0, after R1, R2, R3	Choice to pick and/or process
Balanites aegyptiaca Fruit for human consumption	4	S3	R0, after R1, R2, R3	
Balanites aegyptiaca Pulp for animals if picked	0,75	S3 Not allowed in restoration period	R0, after R1, R2, R3	
Balanites aegyptiaca Oil with picking	2	S4	R0, after R1, R2, R3	
Balanites aegyptiaca Crab with picking	0,2	S4	R0, after R1, R2, R3	
Balanites aegyptiaca hull	0,13	S4	R0, after R1, R2, R3	
Total value of *balanites aegyptiaca* fruit without harvesting (animals collection) but with processing	6,29	S4	R0, after R1 & R2	
Balanites aegyptiaca fruit pulp for animal consumption	1,5	S4	R0, after R1 & R2	
Balanites aegyptiaca Oil	4,	S4	R0, after R1 & R2	
Balanites aegyptiaca oilcake	0,4	S4	R0, after R1 & R2	
Balanites aegyptiaca hull	0.275	S4	R0, after R1 & R2	
Acacia Senegal gum	0,89	S3, S4	R0, after R1 & R2, R3	Picking choices
Acacia Senegal pod	1,26	S3, S4	R0, after R1 & R2, R3	
Acacia tortilis pod	1,6	S3, S4	R0, after R1 & R2, R3	
Wood energy	8,64	S2, S3, S4	R0, after R1 & R2, R3	Collection options

  - indirect use of pulp by animals (70% of total pulp)
  - wood valorization
- S4: High valuation:
  - valorization of herbaceous fodder
  - woody fodder valorization—high (with human intervention)
  - fruit picking and selling (30% of total fruit)
  - indirect use of pulp by animals (70% of total pulp)
  - crushing of the kernels to make oil, valorization of the cake, valorization of woody and herbaceous fodder, indirect valorization of the pulp by the animals, valorization of the sources of energy shells
  - wood valorization

In the restoration scenarios, we consider three situations.

- R0: corresponds to no restoration operation
- R1: a situation of reforestation without economic valuation for 7 years before the opening of the plots (Historical GGW plot in Tessékéré Sénégal (Delay et al., 2022))
- R2: a reforestation situation with straw valorization by an EIG without animal entry (strict prohibition of pruning and no valorization of fruit that has fallen to the ground) for 7 years before the opening of the plots (actual management of GGW plot in Tessékéré Sénégal (Sacande and Parfondry, 2018)
- R3: a reforestation situation with straw valorization by an EIG (strict prohibition of pruning and no valorization of fallen fruits) for 30 years without opening the plots (actual planning management of GGW plot in Widou, Sénégal, field observation May 2022)

We obtain a relationships-matrix between the resource use scenarios (G) and the land restoration modes (R) of 48 scenarios for an evaluation of the return on investment (ROI).

3.4.1 Projection of restoration

We place the potential for success at 30% (allowing for 50 added trees/hectare, for a final density of 65 trees/hectare). We have 20% of provisioning services from 0 to 5 years, 40% of services between 5 and 10 years, 60% between 10 and 15 years, 80% between 15 and 20 years, and 100% beyond 20 years (Mirzabaev et al., 2022). We account for a reduction of one tree per year per hectare for animal feed and energy needs. The removed tree could regenerate naturally. In a fenced pasture, we consider that 50% of the biomass is available for harvesting.

During the restoration process (7 years in R1 & R2) and the conservation process (7 years of restoration and 23 years of

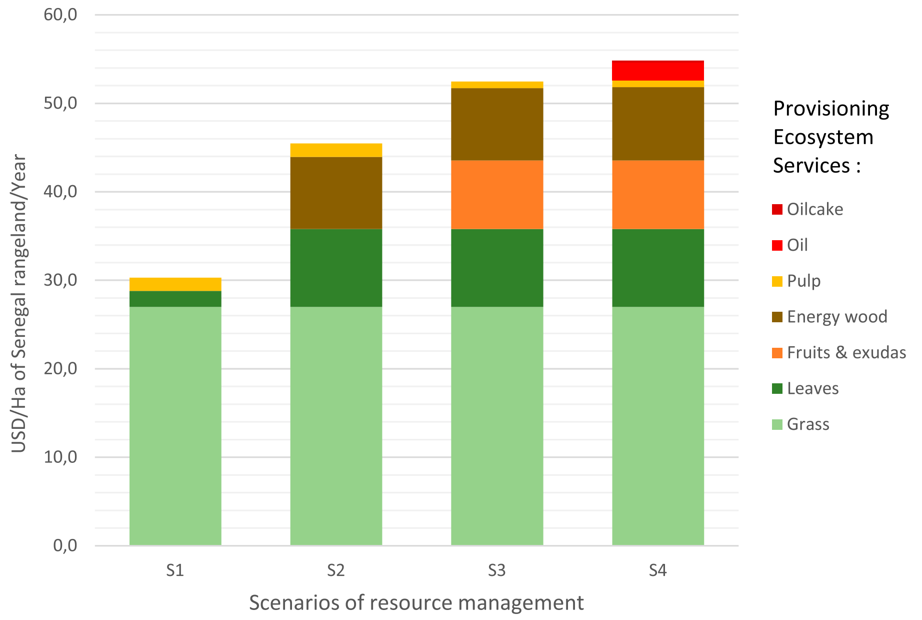

FIGURE 3
Potential value ($USD/ha) of PES by a Senegalese wooded pasture in four scenarios of resource management.

conservation in R3), destocking of timber-wood (for self-consumption or sale) is impossible due to fencing. In R1 & R2, the destocking of timber-wood is still illegal but possible after 7 years. Destocking of trees has an impact on the number of trees inside the plot and the provision of ecosystem services (Figure 2).

4 Results

4.1 Giving value to the restoration of the tree layer in pastoral areas

The reference value of our model is situation R0 (i.e., no restoration operation). Four natural resource management scenarios have been modeled in R0 (Figure 3). According to the data collected, the average value of 1 ha of sparsely wooded rangeland ranges from a low valuation of $30 USD/ha (S1) to a high valuation of $55 USD/ha (S4), representing a minimum of $930 USD and a maximum of $1700 USD over a 31 years span (2020–2050).

Depending on the scenario, the percentage of grass in the value of the pasture ranges from 87% (S1) to 42% (S4) and the percentage of animal feed in the value goes from 100% (S1) to 64% (S4). This shows the importance of the pastoral system's economics in the valorization of natural resources.

The main products of a hectare of savannah in the Sahel are pasture, leaves, fruits, and wood. The value of tree products can represent up to 64% of the value of PES (S4) (Figure 4). The processing of seeds into oil, oilcake, and shells for energy brings a

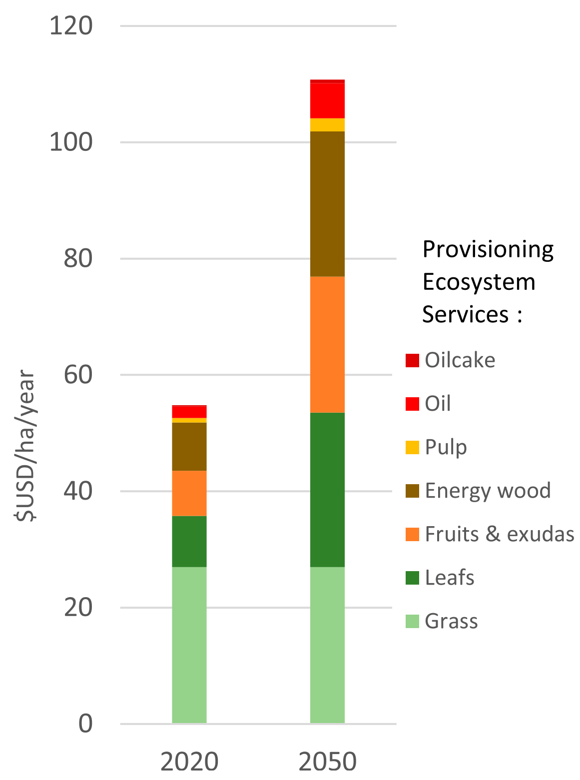

FIGURE 4
Comparison of potential value ($USD/ha) of services provided by a pasture under natural resource management (S4) in 2020 and 2050, post reforestation.

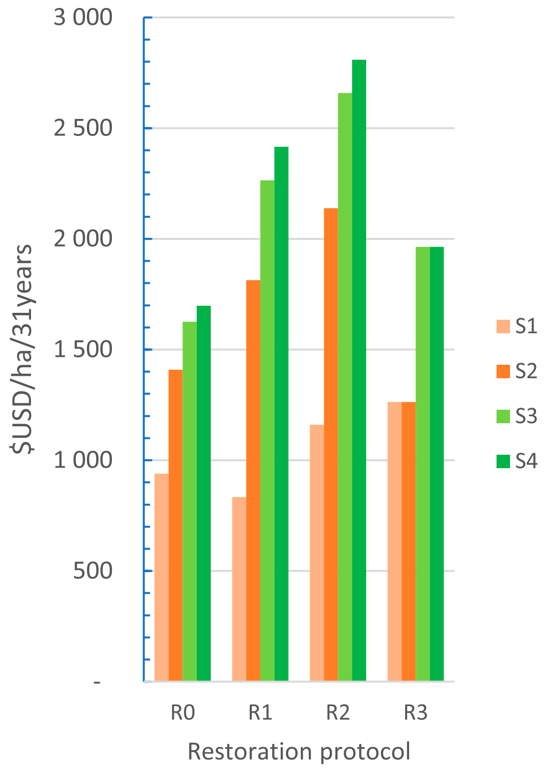

FIGURE 5
Total economic potential of 1 ha of tree pasture over 31 years according to the reforestation protocol (R) and the management scenario (S).

limited value per hectare (+5% between S3 and S4). For a more detailed evaluation of the latter, it would also be necessary to remove the depreciation of the machinery purchased and the fuel costs related to processing.

4.2 Evaluation of the gain in services through reforestation

Projecting the four resource management scenarios into the three restoration scenarios shows that the average value of tree grazing increases from $900 USD to more than $ 2700 USD over 31 years (Figure 5). However, there are major differences between the scenarios (Table 2). The scenario with a fence maintained for 30 years (R3) has lower results than the scenarios with the fence opened after 7 years (R1 & R2), except in the case of a scenario where the resources are used solely by animals (R1-S1 & R2-S1).

The greatest gains in value are obtained in the R1 and R2 restoration situations with high value management scenarios (S3 & S4). However, the total closure of the plots for 7 years (R1) implies a 20% loss in value compared to the model (R3) with the creation of an EIG for straw management and the organization of the harvest during dry season. The R3 scenario is certainly the worst situation with a value almost equivalent to the R0 scenarios without restoration. There are even values below R0 in R3-S2, which means that this form of restoration causes farmers to lose natural capital (25% less than the value in R0-S2). One benefit to scenario R3 is that the woody capital remains intact and thus maintains the level of carbon sequestration. To be fair, this loss should be compensated through other mechanisms. Similarly, between R1 S1 & R0 S1, the enclosure without promotion of sustainable resource management or economic diversification leads to a negative impact on population.

The estimate of productivity gain per hectare must take account of the initial management scenario. Some areas are more suitable for intensive management, such as lowlands that already have a high density of trees per hectare. The socio-economic composition of the households in a territory is also an element to be considered; some areas are more oriented towards pastoralism, but in others, a gathering economy is more developed. The production of new ecosystem services has different effects depending on socio-economic groups and gender-specific activities. Gathering and processing, as well as the recovery of wood energy, are more commonly done by women, while pruning and herding are predominantly carried out by men (James et al., 2021).

4.3 The return on investment calculated from PES: trade-offs to be made

To calculate a value gain in the different situations presented in the reforestation and resource management scenarios, we estimated the return on investment based on an estimated reforestation value of $950 over 30 years (Mirzabaev et al., 2022).

To calculate the gain we needed to compare the value of the starting situation with that of the end situation; this was performed for 16 trajectories coupled with three reforestation scenarios, which gave us 48 different scenarios. We present here the ROI for the same level of management scenarios from the reference situation (R0) to Restoration success situation. The results show that protoctol R1 (restoration without economical benefit) and protocol R3 (restoration for carbon sequestration with economical benefit) gets negative average ROI. The potential PES added to the landscape represent less than the cost of the restoration. Local community cannot invest autonomously into land restoration without support from other economical stakeholders.

Protocols R2 appears to be the most interesting of the three scenarios showing the best average of economic value during the reforestation period and inducing rapid results in S3. Scenarios R1 and R3 require investment in NTFP processing (S4) to be profitable while R2 can be considered profitable at the harvesting level (S3).

According to the 48 scenarios, R1 and R3 have an average ROI of −54% and −78% respectively, whereas R2 has an ROI of −14%. This estimate shows that the closure of areas to pastoralism has a very significant negative impact on the ROI despite the valorization of straw in R3.

To achieve a satisfactory ROI (above 40%), reforestation operations need to invest in the organization of harvesting and processing. This means also investing in NTFP value chains, despite the fact that the value of processed NTFPs and co-products (livestock feed and energy) is only around 20% of the total value of the ecosystem services provided. Both pastoralism and NTFP valuations are necessary to achieve a satisfactory ROI.

TABLE 2 ROI accounting for the benefits of provided services against the cost of restoration at 30 years under the four management scenarios.

		Initial management scenario					
		R0S01	R0S02	R0S03	R0S04	Average ROI for RxS	Average ROI for R
Restoration protocols (R) and final management (S)	R1-S1	−112%	−164%	−188%	−196%	−165%	−54%
	R1-S2	−3%	−55%	−79%	−87%	−56%	
	R1-S3	47%	−5%	−29%	−37%	−6%	
	R1-S4	64%	12%	−12%	−20%	11%	
	R2-S1	−75%	−128%	−152%	−160%	−129%	−16%
	R2-S2	33%	−19%	−43%	−51%	−20%	
	R2-S3	91%	39%	15%	7%	38%	
	R2-S4	108%	55%	31%	23%	54%	
	R3-S1/S2	−64%	−116%	−140%	−148%	−117%	−78%
	R3-S3/S4	14%	−38%	−62%	−70%	−39%	

Legend colors.

Losing more value than the reference of no reforestation.	Gains in value do not cover the complete cost of investment.	Slight gain over investment with no new investment.	Gain over investment with new investment.
(red)	(orange)	(light green)	(dark green)

5 Discussion: limits and lessons learned from ROI modelling of reforestation in the Sahel

5.1 The main limitations of the model

5.1.1 Limitations of knowledge of tree-environment interaction

This first model does not take account of tree densification's effect on the environment or ecosystem services that are not provided due to a lack of knowledge in the Sahelian region. To some extent, an increase in the number of trees per hectare can provide more services but beyond a certain threshold, that increase might no longer have an effect or might even cause the supply of services to decrease (Goffner, Sinare, and Gordon, 2019).

In terms of water infiltration, some studies show that there is a tipping point where increasing the density of trees no longer favors infiltration and can even limit it (Ilstedt et al., 2016; Schwärzel et al., 2020). Efficient infiltration replenishes groundwater, ensuring a more stable water supply for both agriculture and human consumption. It also helps combat soil erosion, enhances vegetation growth, and contributes to the overall resilience of ecosystems in this vulnerable area. Similarly, with regard to woody growth, the increase in tree density could lead to a reduction in the size of the trees and thus limit their capacity to produce wood and non-wood products, or simply to sequester carbon (Harper et al., 2010).

The survival rate of seedlings is a crucial indicator in the Great Green Wall project. However, the GGW survival rate ranges from 20% to 50% at planting and falls below 10% after 3 years (Turner et al., 2023). This leads to a reduction in the potential tree density in reforested areas. By contrast, a commercial agroforestry specialized in Arabic Gum might have higher success rates and tree density due to better technical system. However, high density may impact overall ecosystem services, such as groundwater and carbon sequestration. High-density forests require periodic cuts to ensure proper growth. Finding a balance between seedling survival, tree density, and ecosystem management is crucial for maximizing socio-environmental benefits (Goffner, Sinare, and Gordon, 2019).

5.1.2 Taking account of regulatory, support, and cultural services

We have questioned whether the ecosystem services enabled through reforestation programs can offset or support the costs of restoration. Indeed, a positive ROI enabled by provisioning ES could allow some empowerment of local actors in the conduct of restoration. But the results of our study show that it is difficult to obtain a positive ROI with all provided services, given that some activities are currently illegal (wood cutting, carbonization) and that some activities are highly controlled (pruning and gathering). Taking better account of regulatory, support, and cultural services might be one way of improving the calculation of ROI.

Carbon sequestration is attracting the attention of international donors, with the carbon credit market trending upwards ($10 USD/tonne in 2022) in the face of the need for an energy transition and carbon neutrality by 2030–2050 (Lokuge and Anders, 2022). With estimates of 0.5 tonne per mature tree in the dry zone, sequestration from +50 trees/ha by 2050 show an economic potential of $2000 USD/ha.

Other factors such as soil fertility, humus, return of wildlife, water infiltration, reduction of soil temperature, air improvement, etc. should also be added to the model. Mirzabaev et al. (2022) estimates that regulatory, support, and cultural services could account for 2/3 of the economic value of restoration.

Although this economic perspective is favorable to reforestation, there is a danger. Valuation through regulatory and support services, while largely covering restoration costs, could lead to land-use change and a negative impact on local stakeholders' access to ecosystem and socio-economic services (Mechiche-Alami et al., 2022).

5.1.3 Testing alternative reforestation scenarios in relation to land tenure concerns

One of the levers to increase the ROI of reforestation is to rationalize investment costs in relation to ecological objectives. This article has not addressed all the various costs associated with reforestation operations. Fencing often represents between 25% and 50% of the budget for the installation of operations.

To reduce the cost of fencing, the GGW's historical choice has been to close perimeters of more than 500 or even 1,000 ha as one unit. However, these plot sizes clearly have hindered pastoral mobility and reduced the capacity of the guards to protect the plot. In the face of sabotage, the budget for repairing the fence is as important as the budget for setting it up. Reducing the size of the paddocks results in a higher cost per hectare at installation but reduces maintenance costs and conflicts and improves the potential for the biodiversity corridor.

Several management scenarios could be tested with technical services and local actors to avoid closure of the pastoral land, such as Assisted Natural Regeneration (ANR) or using individual protection with dead wood. These techniques would make it possible to increase the number of trees in the area without having to put up fences. However, they require greater involvement of the local population and therefore better integration of the participation dimension in the management of forest resources (Sacande and Muir, 2022b).

Taking better account of rainfall variability would allow investment in activities that can be adapted to anticipated forecasts.

5.2 The main achievements of the model

5.2.1 Considering pastoralism in the planning of reforestation activities

The results of our analysis show that there can be compatibility between pastoral and reforestation activities. Nevertheless, the land use transformations during restoration are important. The closure of space for reforestation represents a significant loss of resources, especially during lean periods, which are particularly difficult for herders and their animals (Delay et al., 2022). The establishment of EIGs is an action that can reduce the risk of conflicts between herders and technical services.

Straw collection is rarely done without amendments to the plots. Exporting straw from the plots without importing manure can lead to soil degradation and a profound change in herbaceous diversity, especially if the straw is cut before the seeds have had time to fall and increase the soil seed bank. It is recommended to consider the ephemeral nature of straw valorization and to keep the plots open in the long run. If local actors wish to maintain the straw storage function of the reforestation plots, they should be advised to integrate the obligation to bring in amendments in exchange for the right to collect straw.

We have also extended the assessment to the co-products of oil production. These co-products are used in animal husbandry for the production of milk or meat, which have not been included in this estimate. The ROI should be reinforced by taking into account the benefits from the indirect activities related to the restoration.

5.2.2 Investing in support for local actors involved in NTFP value chains

In order to obtain a satisfactory ROI, NTFPs need to be valorized by marketing the fruits or by processing them. The harvesting and processing actors are still very vulnerable and have little organizational capacity or capital for investment. It should be noted that the technical agents of the Water and Forests Department are working to provide better support to these actors in order to insist on sustainable harvesting using appropriate techniques (Sacande and Muir, 2022b). Harvesters are very often associated with charcoal burners and other practices that exploit wood resources. It would be interesting to use territorial management tools such as the pastoral units in Senegal to organize the harvesting sector (Wane et al., 2006). The network of oil processing units could be organized on a regional scale to better distribute the added value in the territory. Including women in new GGW value chains is essential for promoting sustainable development and improving economic and climate resilience (James et al., 2021). By empowering women as active participants in decision-making processes, the project can harness their unique insights and foster long-term success. In this analysis, we have evaluated the ROI at the scale of rural areas, but the added value of NTFP marketing, as for livestock, lies further downstream in the value chains. The GGW could also consider product labelling to assure consumers of fair distribution of added value in the value chain.

6 Conclusion

The growing interest in reforestation and restoration of degraded lands as part of sustainable land management in the Sahel is giving new visibility to ecological sciences in land use planning. There needs to be a better accounting of economic, land tenure, and gender issues in the design and monitoring of operations developed by states, international agencies, and NGOs. Conservation and restoration approaches need to work synergistically with economic sectors in rural Sahel specially extensive pastoralism as one final beneficiary to promote sustainable resource and land use. The construction of a return-on-investment model for the restoration of degraded land in the Sahel is a tool to open discussions with all actors involved in this process of transforming land occupation and use. The model in the article has shown that it is important to maintain the value of natural resources within reforestation plots. Populations need to have an economic interest in socially supporting reforestation. However, there remains a risk of opposition or waning interest in reforestation projects in the years to come. The reopening of ecosystems remains the most promising scenario, even though it requires a compromise in terms of carbon sequestration. It is important to find compromises between ecological benefits and socio-economic sustainability in environments subject to climatic hazards and strong demographic growth.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

J-DC–writting, modelling field survey TM–writting BB–field survey MB–writting ED–modelling and writting ST–writting, modelling and field survey. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1073124/full#supplementary-material

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