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Alternative biodiesel feedstock systems in the Semi-arid region of Brazil: Implications for ecosystem services

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ABSTRACT

The Northeast region of Brazil has low levels of human development and a marginal environment subject to chronic water scarcity. This paper assesses the potential impacts of bioenergy production from local varieties of castor oil plant and jatropha that could reduce the import of energy in the region, while developing its economy. Biodiesel systems based on these crops can be suitable for the Northeast region as they have low water needs, and are either indigenous or have shown excellent adaptation to the local climate. Apart from biodiesel production, the residue from their processing can be a valuable resource usable for biogas production and bio-fertilizers. Using the ecosystem services approach, five land management alternatives are compared: (i) Caatinga woodland (a type of dry savannah native to the region), (ii) a scheme of local jatropha varieties and vegetation for Caatinga forest restoration, (iii) a crop rotation scheme of castor oil plant and cowpeas, (iv) cowpea mono-cropping, and (v) pasture. Based on the analysis of secondary data, some provisioning and regulating services were assessed quantitatively, while others qualitatively. The results suggest that the conversion of (i) cowpea mono-cropping to a rotation of cowpeas and castor and (ii) degraded pastures to a jatropha-Caatinga forest restoration scheme can provide a bundle of provisioning, regulating and supporting ecosystem services. Feedstock for bioenergy is the most important ecosystem service derived from these multi-functional landscapes. In particular converting pasture to a jatropha-Caatinga forest restoration scheme could provide per hectare 0.7 t of oilseeds for biodiesel production and 1.8 GJ of usable energy, in the form of biogas from the residual seedcake. The castor-cowpea rotation scheme could provide per hectare 1.5 t of oilseeds for biodiesel production together with 2.2 GJ of usable biogas energy, per hectare.

1. Introduction

Brazil contains a variety of different biomes and climatic conditions. Caatinga is one of these biomes and is exclusively native to Brazil. It occupies 982,563 km^2 or around 11% of the landmass of the country (Fig. 1), and is characterized by xerophile vegetation such as cacti, succulents, crassulaceous and shrubby trees well adapted to recurrent droughts, poor/marginal soils and brackish groundwater [1].

Situated within the Northeast region of Brazil, which is the homeland of 22 million people, Caatinga is one of Brazil's most endangered ecosystems. While the coastal strip that borders the Caatinga is more humid and fit for agriculture, Agricultural activities in the arid interior are limited to the pasture of goats and cattle and small-scale farming. Extractive activities undertaken by the local population has led to rapid environmental degradation. For example, most of the native shrub forest has been cut down for firewood or to clean land for pasture. Currently, only 0.28% of the Caatinga area is protected as a natural reserve.

At the same time the Northeast region registers some of lowest human development levels and economic opportunities in Brazil. It has to import most of the gas, fuel and electric power needed from the rest of the country. In this context, renewable energy resources are assets that could promote the sustainable development of the region. For example, the region has an enormous solar energy and wind power potential that could make it a net-electricity exporter in upcoming years [2,3]. Furthermore, while the cultivation of biofuel crops is not as extensive as in the Centre-West or Southeast regions, the Northeast can play a major role in the cultivation of biodiesel feedstock.

The Brazilian Program for the Production and Use of Biodiesel (PNPB) was launched in 2004. Among its goals was to involve small

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Fig. 1. The Caatinga biome.

farmers of the Semi-arid region in biodiesel feedstock production [4]. Since then, the mandatory blending of biodiesel in the country has risen to 7% (B7) in 2016, and is on track to reach 10% (B10) by 2020. However, despite this impressive uptake of biodiesel, the current feedstock production patterns are quite different than what was expected at the early stages of the PNPB. According to the Brazilian National Agency of Petroleum, Natural Gas and Biofuels, biodiesel feedstock production is dominated by soy (around 70%) and bovine tallow (around 20%), while castor oil plant and jatropha have currently no participation in the biodiesel production [5]. Castor oil has remained a raw material for the pharmaceutical and cosmetics industry, while jatropha, following initial optimism, failed to arouse any commercial interest partly due to its widespread collapse in Africa, India and Southeast Asia [e.g. 6,7]. When scrutinising the results of the PNPB over the past decade [8], it can be inferred that a program designed to empower family-owned farms through their integration in the biodiesel production chain ended up benefitting soy producers, mainly corporate farms from outside the Semi-arid region.

However due to the prevailing climatic condition some neglected biodiesel feedstocks could still play a role in the Northeast. The castor oil plant (*Ricinus communis*, referred to as castor for the remainder of the paper) and different jatropha varieties are already present in the region and have showed good adaptation to the local climate and soils, as well as the ability to coexist with either locally grown food crops (for castor) or the native shrub forest (for jatropha). Regarding the latter, there are several endemic varieties of jatropha in the Caatinga biome such as *J. mollissima* (34% oil content), *J. mutabilis* (39% oil content) and *J. ribifolia* (33% oil content) [9,10].

When it comes to castor, there is a well-established cultivation and commercialization chain based on family farm cooperatives that make Northeast Brazil the second highest producing region of the world, behind only India. Furthermore, castor shows complementarities with cowpea, maize and other crops in terms of sow/harvest cycles and soil nutrients, which point to interesting intercropping (crop rotation) possibilities (Section 3.1.2).

On the other hand, the agro-industry for jatropha has not yet been developed. However the endemic varieties of jatropha could act as nurse plants for Caatinga vegetation by facilitating the development of native plant species beneath their canopy as they can offer benign microhabitats that are more favorable for seed germination and seedling recruitment than the degraded pasture or farmlands found in the region [11–13].

The aim of this study is to identify the potential trade-offs of biodiesel production from oilseeds adapted to the semi-arid climate of the Caatinga biome. In particular, this study assesses the potential impacts of two alternative ways to cultivate such oilseed species: (a) castor intercropped with cowpea and (b) local jatropha varieties combined with Caatinga native vegetation to restore forest in degraded pasture lands. The former has gained some prominence in the Northeast [14], while the latter is a novel proposal that could have some benefits.

In order to identify the main trade-offs expected to emerge following the conversion of common agricultural/livestock land uses in the Northeast with the two feedstock production systems, this study adopts the ecosystem services (ES) approach (Section 2). Given the lack of significant feedstock production in the area using the studied modes of production, it provides an analysis based on secondary data collated during an extensive literature review (Section 3). Section 4 summarises the main expected trade-offs for different types of ecosystem services and outlines some of the key research gasps and challenges promoting further these production models.

2. Methodology and ES mechanisms

To identify the main trade-offs of biodiesel production through the two studied schemes, the ecosystem services approach is adopted [15,16]. The ES is a powerful framework both for the synthesis and meta-analysis of biofuel impacts [17,18] as well as for the assessment of the impacts arising from landscape transformation for biofuel production [19,20].

Initially, an extensive literature review is performed to identify the ecosystem services and disservices provided by these biodiesel landscapes, as well as the mechanisms through which these services/disservices emerge (Sections 3.1.3 and 3.2.3). Subsequently the ecosystem services/dis-services provided by feedstock systems are compared to those of the reference land uses prevalent in the Northeast, i.e. pasture and single-crop farmlands (Section 4.1).

Considering the main expected ecosystem services affected by biofuel expansion [18,21,22], it is hypothesized that the conversion of monocultures or extensive pasture in Northeast Brazil with combined feedstock-food or feedstock-forest restoration schemes respectively, can provide a wider bundle of ecosystem services. These can include:

- provisioning services such as biodiesel feedstock and food crops
- regulating services such as carbon sequestration, and pest and disease control
- cultural services such as ecotourism or the valorization of a unique landscape
- supporting services such as habitat provision, soil protection and nutrient cycling,

While effects on some ecosystem services such as feedstock/food production and carbon sequestration are quantified on a per hectare basis through secondary data collected from the literature, other ecosystem services trade-offs such as pollination or soil protection are compared qualitatively. Results are summarized within an impact matrix (Section 4.1) as such an approach has been used previously to consider the ecosystem services implications of land-use change due to the production of second-generation bioethanol feedstock [23]. Fig. 2 graphically summarizes the study methodology.

3. Characteristics of the studied biodiesel schemes

3.1. Castor oil

3.1.1. Status, potential and barriers for biodiesel production in Brazil

Castor is produced widely in Brazil, with the Semi-arid region being responsible for 3.5% of global production in 2014 (Fig. 3). Castor has traditionally been used for ornamental purposes and for oil extraction, as its seeds can contain 40–50% of vegetable oil.

Currently, castor cultivation and processing is predominantly undertaken by small farmers, often associated in small cooperatives. Due to its unique characteristics castor oil can be used in several value-added industrial products [24], including promising medicines derived from its toxins [25,26].

In terms of climate, castor has shown an excellent adaptation to the Brazilian Semi-arid region. It thrives preferentially in soils with medium texture, either flat or low sloped, that are not very loamy. Clay loam soils with pH between 6 and 7 are ideal for the castor oil plant, which does not yield well in poor or waterlogged soils. Its biggest advantage in the climatic context of the Semi-arid Region is its radicular system, which allows the plant access deeper layers of soil compared to other annual crops such as soy, maize or beans. This can increase the aeration as well as the water retention and distribution capacity of the soil [27]. The ideal annual rainfall for the castor oil plant is between 750 and 1500 mm, with a minimum of between 600 and 750 mm during all the cultivation cycle, followed by 400–500 mm until the beginning of flowering [27].

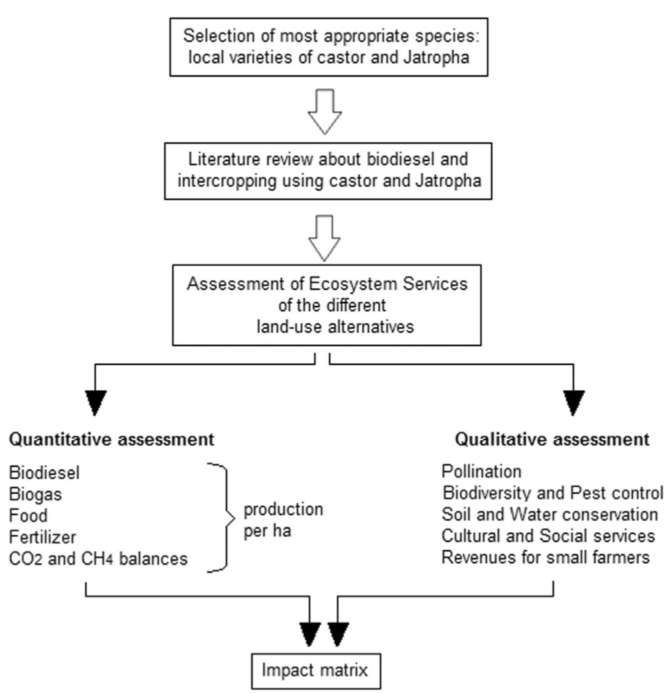

Fig. 2. Methodology flowchart.

However despite these agronomic advantages castor oil has not become an important part of the PNPB [29,30]. This can be explained through diverse reasons ranging from the extended period of drought (2010–2013) that significantly affected harvests, to episodes of corruption among farmer cooperatives [31]. However, perhaps the key reason might have been economic, and in particular the competition of castor oil with soy. Castor oil is primarily used in the cosmetic and pharmaceutical industries, which results in high selling prices. On the other hand soy is produced in corporate farms at very low costs (Section 4.3).

There are also two technical barriers for the production of biodiesel from castor oil, its high viscosity and high final acid number [32]. The first can be overcome by diluting castor oil in a mixture of other vegetable oils (e.g. coconut, soy and cotton oil), at a maximum blend of 30%. The second barrier does not affect the potential of castor oil as a biofuel feedstock as the final fuel is a B7 blend whose minimum content is 7% biodiesel and 93% petroleum diesel in Brazil (the content of biodiesel will be increased to 10% in the next years, B10).

In order for castor to become a competitive feedstock for the local biodiesel industry, its price should reduce either by increasing supply and/or by decreasing production cost through harvest mechanization. Despite the valuable existing experience producing castor in the Semi-arid region, it is not yet clear (Section 4.2) how castor oil could compete with other oils whose biodiesel/diesel blends have satisfactory properties and, more importantly, are less expensive, e.g. soy oil [33], palm oil [34] or others [35]. However, the incentives of the Brazilian Government for castor oil production have brought some benefits in terms of building a knowledge base of how it performs within the ecological, agricultural and socioeconomic context of the Semi-arid region.

3.1.2. Rotation of castor with food crops

Most vegetable oils used for biodiesel (e.g. soy, oil palm, coconut) are important elements of the food industry. This can lead to undesirable competition between food and fuel through the direct diversion of the crop for biodiesel production [44]. On the other hand, the main uses of castor oil are in the cosmetics and pharmaceutical industries, reducing this direct competition with food production.

What makes castor oil more appealing for minimizing indirect food-fuel competition (e.g. diversion of land, water, labour and other agricultural inputs, [44]) is that in the context of the Semi-arid area, castor could be cultivated in crop rotation schemes with food crops such as maize, beans (cowpea) and soy.[1] This can reduce to an extent the competition between feedstock and food production [44]. Table 1 illustrates the complementarity between castor oil plant and food crops common in the Semi-arid region.

Table 1 also illustrates two rotation schemes where castor has a small agricultural cycle of 7–8 months after an annual cowpea harvest (for small farmers in semi-arid lands) or after an annual soy harvest (for the more fertile soy plantations). In some regions,

[1] Castor offers poor complementarity with other food crops such as grain sorghum (*Sorghum bicolor* L. *Moench*) [14].

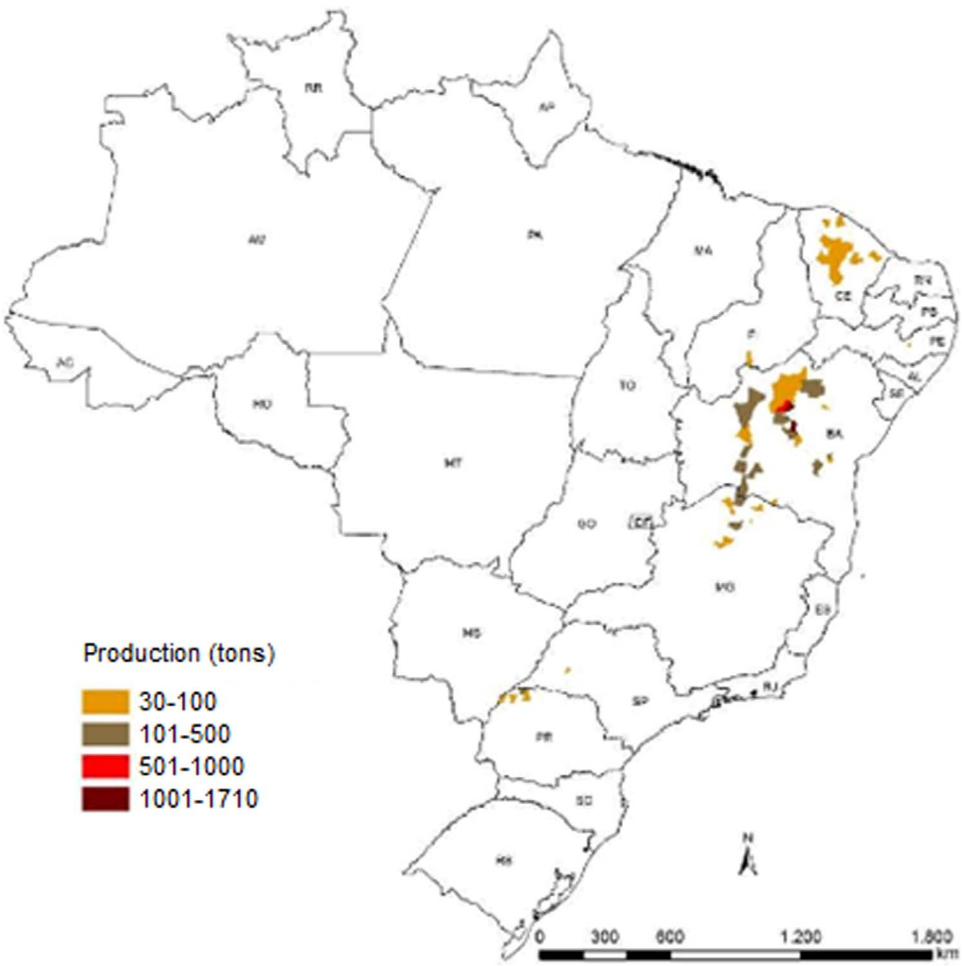

Fig. 3. Main producing regions of castor oil [28].

Table 1
Agricultural complementarity cycle castor (*Ricinus communis* L.), maize (*Zea mays L.*), cowpea (*Phaseolus vulgaris L.*) and soy (*Glycine max*) in the Northeast region of Brazil [28].

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Castor												
Maize (1st harvest)												
Maize (2nd harvest)												
Cowpea (1st harvest)												
Cowpea (2nd harvest)												
Cowpea (3rd harvest)												
Soy												
Rotation scheme 1	Cowpea (1st harvest)				Castor					Cowpea (1st harvest)		
Rotation scheme 2	Soy				Castor					Soy		

Sowing Harvesting

there is also the possibility of a third scheme consisting of cowpea/castor/maize rotation.

In Northeast Brazil, there are two annual rain-fed cowpea harvests. The first occurs during the rainy season (February-May), the second during drier months (June-July), while an additional third is only possible through irrigation in fertile lands. Cultivating castor after the first cowpea harvest implies the substitution of the second rain-fed cowpea harvest, while in the case of soy implies in some cases the substitution of maize (2nd harvest).

Such crop rotation systems using complementary species can be of capital importance in semi-arid environments as a method of maintaining favorable soil characteristics. Castor offers further benefits in this respect considering its low irrigation requirement which can help prevent the soil degradation caused by the accumulation of salts. Finally, a rotation scheme of maize, castor and the forage crop *Brachiaria ruziziensis* (Congo grass) can improve soil water retention level [36].

3.1.3. Effects on ecosystem services

Oilseeds (castor) and food crops (cowpea) are the main provisioning ecosystem services provided by the intercropping system described in Section 3.1.2. As castor oil is not edible due to its toxicity, there is no direct diversion of food to biofuels. However the castor oil plant competes to an extent with cowpea for land as it reduces the available harvests of cowpea in the crop calendar year (Section 3.1.2). In this case castor would replace the second cultivation cycle of cowpea, which is 15% less productive compared to the first harvest as it occurs during the drier months [28]. Overall, this would result in reduced provision of food from the intercropping system by as much as 46% compared to a cowpea monoculture.

Still a castor-cowpea rotation scheme could deliver annually 1.5 t/ha castor oilseeds and 1.1 t/ha cowpea [28,37], reducing to an extent the competition between biofuel and food production, when compared to a feedstock monoculture.

However, castor yields can depend significantly between different varieties (Table 2). The Brazilian Agricultural Research Corporation (EMBRAPA) has developed two castor varieties that provide reasonably high oil yields under the non-irrigated dryland conditions encountered in the Northeast. The “BRS Nordestina” variety was developed in 1990 for manual harvest while the “BRS Energia” variety was developed in 2004 for mechanized or manual harvest. The varieties “BRS Nordestina” and “ BRS Paraguaçu” have cycles of 250 days (from sowing to harvesting) with potential yields of 1500 kg/ha when cultivated in non-irrigated drylands.

Table 2
Characteristics of castor plant varieties adapted to the Semi-arid region.
Source: [14,28,38–40]

Variety	Rainfall (mm)	Yield (kg/ha)	Oil percentage	Weight of 100 seeds (g)
BRS 149 Nordestina	188	230	45.90%	45.3
BRS 149 Nordestina	571	899	46.50%	50.0
BRS 149 Nordestina	700	1500	46.90%	54.3
BRS 149 Nordestina	897 (rainfall + irrigation)	2760	48.10%	60.1
BRS Energia	188	230	46.20%	23.5
BRS Energia	897 (rainfall + irrigation)	2820	49.30%	28.9
Pernambucana	700	1300	47.28%	68
Baianita	700	1150	47.49%	68
SIPEAL 28	700	1130	47.47%	76
BRS 188 Paraguaçu	913 (rainfall + irrigation)	2872	52.60%	57.8
BRS 188 Paraguaçu	571	1048	47.72%	47.1

The crop rotation system discussed in Section 3.1.2 is appropriate for the non-irrigated/rain-fed conditions encountered in the semi-arid areas of Northeast Brazil. When it comes to the effects of the different land uses on water availability, there seems to be no overlapping between the different crops that could impact the water resources allocated for food production. Experimental data collected in the region show that under the same soil and rainfall conditions, cowpea and castor have almost the same water requirements. The average daily evapotranspiration is 4.24 mm/day for cowpea and 4.12 mm/day for castor (this is to achieve yields of 1.1 t/ha and 1.5 t/ha respectively) [41,42]. Moreover, studies of crop rotation and intercropping schemes of cowpea, castor and other crops commonly found in the region, indicate that such farm management practices reduce the overall water requirements compared to mono-cropping systems [43]. Specifically, it was found that a rotation schedule with complementary crops minimizes soil exposure, decreases surface temperature and evapotranspiration and maintains soil moisture during the dry season [43]. The above suggest that sacrificing one cowpea harvest for castor production will most likely not reduce the available water for other uses.

The above crop rotation system can have different effects on regulating ecosystem services. Castor production under this rotation system essentially means the establishment of feedstock production on previous agricultural land. This implies that there will not be a significant change in carbon stocks, as several studies have identified that the conversion of agricultural land for feedstock production creates low carbon debts [44,45]. This means that no significant effects (whether positive are negative) are expected for climate regulation services linked to carbon sequestration.

Crop rotations can affect the flow and stability of natural pest control services [46]. The rotation of castor in the above scheme can possibly provide regulating ecosystem services in the form of weed [47] and nematode [48] control. Cowpea is susceptible to nematodes and should therefore not be planted consecutively on the same land as it increases the risk of infestation [49]. Soy, maize and cotton are also susceptible to harmful nematodes [50]. Rotation of such crops with nematode-resistant species such as the castor oil plant can potentially reduce parasitic nematode infestations [48].

The above crop rotation system can potentially provide soil-related ecosystem services such as erosion regulation, fertility maintenance and pollution regulation. Regarding erosion regulation, crop rotation with castor can reduce the exposure of bare soil. Current cowpea production practices fallow the land between two consecutive cowpea harvests as a method of conserving moisture. As castor has a longer growth cycle than cowpea, the soil benefits longer from the protective action of plant cover [28]. Furthermore, castor has a powerful radicular system that can bind soil better thus controlling better erosion [51]. When it comes to soil fertility, sometimes in the prevailing cowpea production practices in the Northeast, agricultural residues are burnt or left to rot on field to fertilize the soil [52]. When intercropping with a crop that helps fix nutrients to the soil such as castor, these nutrients can be used for the next cowpea cycle. Regarding soil pollution regulation, castor has high soil remediation potential, as it possesses an excellent ability to extract toxic metals and some organic contaminants such as pesticides [53–55].

Land use/cover change from a cowpea monoculture to cowpea alternated with castor could also bring benefits in terms of biodiversity. It has been shown that crop rotation can have positive effects for local biodiversity [56,57]. In the Semi-arid Region of Brazil agronomic tests of novel farming system based on (i) crop rotation (castor and cowpea), (ii) avoidance of herbicide use and (iii) avoidance of slash-and-burn for land clearing, have shown a significant increase in biodiversity and a low incidence of pests after only two years [43].

While crop-rotation systems can be more accommodating to biodiversity, some of these schemes can have a neutral or even negative effect on some pollinator species. For example castor contains toxins such as flavonoids, ricinine and ricin. Flavonoids from castor have insecticidal activity against the Coleoptera *Callosobruchus chinensis* [58]. Ricinine has a proven activity against *A. mellifera* [59], the Hymenoptera *Atta sexdens rubropilosa* [60], and the Lepidoptera *Spodoptera frugiperda* [61]. Studies in the Brazilian Semi-arid Region have concluded that the expansion of castor bean for biofuel production might be potentially hazardous to native and domestic honey bees, as castor pollen was found to be toxic to bees under laboratorial conditions [62]. As a result local pollinator species such as wasps, ants, bees or butterflies may decline in castor-dominated landscapes, reducing as an extent the pollination ecosystem services they provide. However, more extensive studies under natural conditions are needed to establish the actual effects of castor and castor pollen on pollinators, and thus on pollination services.

3.2. Jatropha

3.2.1. Jatropha as a biodiesel crop in Brazil: Status, potential and barriers

Jatropha species are well adapted to tropical climates of South America. For example, the Caatinga biome hosts some endemic varieties such as *J. mollissima, J. mutabilis* and *J. ribifolia.*

Jatropha can be cultivated from the sea level to altitudes above 500 m, adapting itself to survive in very poor dry soils under conditions considered marginal for agriculture [63]. It is a perennial plant whose harvesting period extends for around six months. Several of the early literature has highlighted that jatropha cultivation can have advantages such as the lack of need for pesticides and the ability to provide reasonable yields in low-fertility soils and under arid conditions [64]. It has also been suggested that different annual crops can be introduced within the available space between jatropha plants to minimize competitions with other food and industrial crops. Candidate crops include rice (*Oryza sativa L.*), maize (*Zea mays L.*), cassava (*M. esculenta C.*), peanut (*Arachis hypogaea* L.), cotton (*Gossypium hirsutum L.*), cowpea (*Phaseolus vulgaris L.*) and crambe (*Crambe abssynica H.*) [65–68]. This coexistence between jatropha and other crops has been stimulated in the Semi-arid Region of Brazil by programs that aim to empower small family-owned farms [68].

Jatropha oil can undergo transesterification to produce biodiesel [69,70]. However jatropha has experienced a wide collapse (or underperformance) in practically every country that was promoted as a biofuel crop including Mexico [71], Indonesia [72], India [73], China [74] and several parts of sub-Sahara Africa [6] such as Ghana [125]. This accumulated knowledge has suggested several factors including the undomesticated nature of the crop and the inability to deliver optimum yields without good management practices, among several others [6,125].

As in other parts of the world, jatropha raised expectation in Brazil in the early 2000s as a potential biodiesel feedstock [68,75,76]. Back in 2007 the potential of the plant was not questioned but it was highlighted that yields were not predictable, that the conditions best suiting its growth were not well defined and that the potential environmental impacts of large-scale cultivation were not understood at all [77]. During the last decade, studies have better characterized local jatropha varieties in Brazil [9,10] and different cultivation schemes that could produce in the region on average 500 L of oil per hectare [66,68]. In the rainfed conditions of Northeast Brazil jatropha seeds could be competitive compared to other oilseed crops that need irrigation such as soybeans or rapeseeds which produce lower oil by weight [78] and lesser yields of biodiesel after transesterification [79]. These competitive advantages could be further increased with mechanization to reduce production costs during harvesting and shelling [78,80] or even with biotechnological improvement [81,82] but the eventual yield and economic performance can be still unpredictable.

In 2010 a specific program for the assessment of jatropha possibilities in Brazil was initiated (BRJatropha) [83]. Its aim was to create a germplasm bank with the most resistant jatropha seeds, to find ways to detoxify the waste seedcake in order to be used as fodder and develop low-cost jatropha biodiesel production systems in the Semi-arid region. The BRJatropha Project ended in 2014 and generated valuable knowledge, especially regarding the highest-yielding varieties for the region [84]. Yet, despite this initiative and some efforts from local farmers and entrepreneurs, the commercial cultivation of jatropha largely failed in the region.

3.2.2. Jatropha as a nurse plant for Caatinga restoration

While jatropha has failed to gain acceptance in Northeast Brazil as a biodiesel feedstock (Section 3.2.1), it can offer a possible alternative for the restoration of the Caatinga native forest in degraded and low-productivity pastureland and farmland located on marginal soils. Adult specimens of local jatropha varieties can act as nurse plants, having a positive effect on the emergence and survival of seedlings and on the surrounding microclimate [9,12,85–88]. If jatropha plants are combined with local shrubs, its beneficial effects on microclimate can be possibly reinforced, as under drought conditions these xerophile plants may increase soil nutrient and moisture content and act as a buffer against high radiation and high temperatures [11]. The importance of facilitative interactions between local species increases as environmental conditions become more stressful [11].

The effect of jatropha as a nurse plant has been documented in several regions of the world. In semi-arid zones of Mexico, for instance, *J. dioica or J. cinerea* and *J. cuneata* act as colonizer species on degraded soils. Those species have been reported to associate with arbuscular-mycorrhizal fungi and help to stabilize windborne soil that settles under dense plant canopies, thus enhancing the establishment of further colonizer plants in bare soils of disturbed areas [89,90]. In the Northeast of Brazil, reforestation of Caatinga has been mostly done through the use of different mesquite varieties (*Prosopis julifora*) which are invasive species. But even in those cases, *J. mollissima* (a local jatropha variety) has been constantly encountered among the new colonizer plants established in the reforested areas [85].

Based on this identified potential of jatropha as a nurse plant, a novel feestock system based on the plantation of scattered adult specimens of local jatropha varieties in combination with local xerophile shrubs found in the Caatinga might be promising. Such a landscape could look like Fig. 4, but with a lower density of jatropha trees and with local shrubs intercropped among them.

Based on the growth rates of Caatinga flora such a feedstock landscape could be harvested only during the first 10 years. In other words, jatropha would act as a cash crop during the initial stages of forest restoration, before the densification and consolidation of natural Caatinga woodland turns oilseed harvesting impracticable.

Fig. 4. Young *J. curcas* plantation surrounded by native Caatinga forest in Northeast Brazil.

Table 3
Local jatropha varieties and their pollinators.
Source: [103]

Local jatropha variety	Pollinators
J. ribifolia	*Apis mellifera* (European honey bee) *Trigona spinipes* (bee) *Xylocopa grisescens* (bee)
J. mutabilis	*Apis mellifera* (European honey bee) *Trigona spinipes* (bee) *Xylocopa frontalis* (bee) *Chlorostilbon lucidus* (hummingbird) *Anopetia gounellei* (hummingbird)
J. mollissima	*Apis mellifera* (European honey bee) *Trigona spinipes* (bee) *Xylocopa frontalis* (bee) *Chlorostilbon lucidus* (hummingbird) *Anopetia gounellei* (hummingbird) unidentified bats

3.2.3. Effects on ecosystem services

Jatropha seeds are the main provisioning ecosystem service provided by the jatropha systems described in Section 3.2.1. The extracted oil can be used for a number of products such as feedstock for biodiesel and raw material for soap.[2] Average seed harvest for this region can be 1.5 t of seeds per hectare corresponding to 500 L of oil (33% oil content) [68]. After reaching maturity (2–3 years after planting), jatropha plants can be productive for approximately 40 years.

The conversion of pasture to a Caatinga-jatropha restoration scheme could reduce the production of livestock-related provisioning ecosystem services. Non-degraded semi-arid pastureland in the Northeast can support on average 2 heads of cattle per hectare, producing each year an average of 100 kg of meat [92]. On the other hand, Caatinga areas can provide habitat to pollinators, with jatropha trees being a food source to these pollinators (see below). As a result some limited amount of honey might be a possibility for restored Caatinga-jatropha landscapes.

Currently Caatinga areas are used to extract timber and fuelwood (Section 1). A fully restored Caatinga landscape can potentially become able to provide such provisioning ecosystem services again. However given the current unsustainable trends of fuelwood and timber extraction from Caatinga woodlands (Section 1), it is not possible to ascertain the long-term sustainability of receiving such provisioning ecosystem services from restored Caatinga-jatropha landscapes.

The Caatinga-jatropha forest restoration system will be under rainfed conditions. As jatropha has been identified to be a conservative water user in Africa savannah contexts, it is not expected to compete with natural vegetation for water [93]. In the Caatinga context, the three jatropha varieties considered in this paper are endemic (*J. mollissima*, *J. mutabilis* and *J. ribifolia*) and tend to maximize local water resources by creating synergies between other plant species and rhizosphere microorganisms [9,10,12]. As a result the cultivation of jatropha trees at low density for forest restoration is not expected to reduce water availability for other natural and human uses.

Land use change associated with landscape conversion for biofuel production can have significant effects on carbon stored and the carbon sequestration potential of the converted landscape [94]. Research in Africa has shown that jatropha production can produce significant carbon debts if it is established in semi-arid savannah or virgin Miombo woodland, e.g. see [95] for a review of the literature. On the other hand it can produce carbon gains if it is established on agricultural land, i.e. as hedges demarcating agricultural plots [96]. In the context of conversion of semi-arid woodlands in Brazil, unpruned *J. curcas* plantations were confirmed to store on above ground biomass 3 t of carbon per hectare. Still such carbon stocks are lower than those of mature Caatinga woodland estimated at 14–35 t of carbon per hectare [97,98].

Conversion of degraded pasture or farmlands to native restored forest could have a clear positive impact on several soil related regulating services. Some authors have noted that jatropha as a tree species can reduce the overall time of bare/exposed soils due to harvesting and regrowth compared to annual or perennial crops [95]. This, in combination with the gradual restoration of native woodland, guarantees a continuous plant cover compared to cowpea monocropping [99] and natural pastures [91]. In the Semi-arid region, the exposure of bare soil is one of the main factors contributing to desertification, and this is why agroforestry systems have proven to perform better in terms of soil and water conservation compared to intensives land uses such as mono-cropping and pasture [100]. The latter has a very negative effect on soil conservation as 73% of natural pastureland in the region are highly degraded due to the systematic use of unsustainable stocking rates that exceed the pasture's ability to recover from grazing and stomping [92]. In this respect, jatropha trees limit livestock movement and stabilize contour bounds [101,102], potentially acting as live fences if planted densely.

As degraded pastureland is progressively transformed into Caatinga forest, biological diversity should increase due to the restoration of the natural habitat. Furthermore, local varieties of jatropha (*J. mollissima, J. mutabilis* and *J. ribifolia*) can support different pollinator species such as insects, hummingbirds and even bats (Table 3). In particular, *J. mollissima* and *J. mutabilis* are able to support the most pollinator species (Table 3). However this can have an interesting trade-off. While *J. mutabilis* can attract honeybees, and as a result contribute to honey production (see above), *A. mellifera* displaces local pollination species through the depletion of the flower resources. Thus plants that depend exclusively on local pollinators could be negative impacted.

3.3. Co-products and co-benefits

Oil extraction from castor and jatropha seeds generates seedcake rich in protein and carbohydrates as a waste residue. Jatropha seedcake contains around 49% carbon (C), 6% hydrogen (H) and 3% Nitrogen (N) [70,104–106]. Annually, the castor oil industry generates around 90,845 m^3 of waste castor seedcake in the Northeast region that are left to rot around extraction facilities, acting as an organic fertilizer [107]. This residue corresponds to 43% of the seed weight. Castor oil seedcake has a nutrient content of: 6.5% Nitrogen (N), 2.0% Phosphorous (P) and 1.0% Potassium (K).[3] In addition, the fertilizer produced by castor seedcake retains the capacity to control soil nematodes [48].

Seedcake can also be used for energy production. Both jatropha and castor seed cake can be burned directly, as their residue has a calorific value of 18.8 $MJ{\cdot}kg^{-1}$ [107]. This is relatively high for a solid biomass waste, close to eucalypt wood (19.2 $MJ{\cdot}kg^{-1}$) and much higher than other agricultural or forestry residues such as sawmill waste (10.0 $kcal\ kg^{-1}$) or sugarcane bagasse (9.6 $kcal{\cdot}kg^{-1}$). Seedcake can also be fed in bio-digesters [70,104–106,108,109], which through anaerobic fermentation can yield biogas with methane content as high as 70% [104–106].

Other potential uses for seedcakes include the production of amino acids, glue, pesticides, inks, fibers and bioplastics among others, although further research is still needed [110]. Due to their toxicity castor and jatropha seedcake cannot be directly used as animal fodder. While toxic substances could be removed through expensive physical,

[2] It has been suggested that in some African contexts the economic returns from soap-making are far higher than the sale of jatropha seeds for fuel production [91].

[3] That is, for each ton of castor or jatropha seeds, around 430kg of seed cake containing 28kgN, 8.6kgP and 4.3kgK are generated. In comparison, cow manure has a typical nutrient content of 0.6% N, 0.4% P and 0.5% K. That is, degraded pastureland that contains on average 2 heads of cattle per hectare and receives 1.8t of manure annually is fertilized with 10.8kgN, 7.2kgP and 9kgK.

Table 4
Values for the biodiesel, biogas and biofertilizer processes.

Oilseed	Transesterification		Biodigestion				
	Oil content	Conversion to biodiesel / glycerol	% weight expelled as seedcake	biogas yield (Nm^3/kg seedcake)	NPK content (%) in the bio-fertilizer		
					N	P	K
Castor	47%	90% / 10%	43%	0.15	6.5	2.0	1.0
Jatropha	30%	90% / 10%	70%	0.15	3.0	0.7	1.5

Note: Nitrogen (N), Phosphorus (P), and Potassium (K).

thermal or chemical processes, this makes their use as fodder economically uncompetitive [111,112].

3.4. Values considered for the quantitative assessment of provisioning services and co-benefits

This section describes the secondary data used for assessing the ecosystem services provided by the different land uses as identified in the literature (Sections 3.1.3, 3.2.3). For both biofuel chains, the primary product considered is biodiesel from the transesterification of oil derived from castor and jatropha seeds. For the transesterification process a yield of 90 L of biodiesel and 12 kg of glycerol for each 100 L of oil input is considered [53,54] (Table 4).

The secondary product of the biodiesel production chain is biogas. Selecting biogas as the secondary product is justified because it can enhance resource recovery from agricultural residues of the primary biodiesel chain. This includes both energy recovery from biogas combustion and bio-fertilizers from the anaerobic process. This way it can add multiple possible co-benefits to biodiesel production, making it more appealing to investors. For the biodigestion, a hydraulic retention time of 15 days is considered, which could yield an average 0.15 Nm^3 of biogas per kg of waste seed cake (Table 4).

Average crop and oilseed yields in the Semi-arid region under rainfed conditions (700 mm) are considered as 1.5 t/ha for castor cultivated in rotation with cowpea, and 1.5 t/ha for a dedicated jatropha plantation [36,37,68]. For the jatropha-forest restoration system proposed half that yield (0.75 t/ha) was assumed due to the lower density of trees than a conventional plantation. For pastureland, an average of 2 heads of cattle per hectare (beef cow) was assumed, producing each year an average of 100 kg of meat, 6 kg of tallow (that can produce 5 L of biodiesel), 1800 kg of manure and 110 kg (164 Nm^3) of CH_4 [92]. In order to compare the different types of food output from the alternative land uses, their (annual) yield per hectare is converted into Kcal per hectare, using the following conversion: 1900 Kcal/kg cowpea, and 4000 Kcal/Kg beef meat.

Regarding CO_2 sequestration service, the carbon stored in the above and below ground biomass was assumed to be 14 t/ha [98,113] (other scholars estimate it as high as 35 t/ha [97]). The carbon stored in jatropha trees located in converted native forest has been estimated between 3 t/ha (unpruned trees) and 8 t/ha (for more dense plantations with pruned trees) [97]. In this study, it is considered to be 4 t/ha for the Caatinga-jatropha forest restoration scheme. For cropland and pastures, data from the literature suggest a carbon stock of 4 t/ha [98], but this value could be slightly higher for the latter. Soil analysis in different landscapes in the region have indicated that pasture systems harbor more efficient soil microbial communities in terms of carbon use. Considering the above, land conversion from Caatinga to cropland may cause significant carbon loss from soils [98], but conversion to pasture may increase carbon storage in soils [114]. For the castor-cowpea rotation scheme, there is most likely an insignificant change in carbon sequestration services.

CO_2 sequestration is the regulating ecosystem service associated with CO_2 being stored into plants. All the five considered landscapes act as carbon pools storing an amount of CO_2 in their biomass that ranges from 4 t/ha (pastures and farmlands) to 14 t/ha (Caatinga). Vegetation (living plant biomass), dead wood, litter and soil organic matter act as the major carbon pools. Besides the carbon stored in biomass and soil, each of these landscapes exhibits different rates of carbon influx.

Satellite and direct measurements have shown a net positive influx of CO_2 in all of the five land uses [98,115]. According to these degraded pasturelands or agricultural lands have a carbon influx of 0.4 $t \cdot ha^{-1} \cdot year^{-1}$, a jatropha plantation has 0.8 $t \cdot ha^{-1} \cdot year^{-1}$ whilst Caatinga forest absorbs 2 $t \cdot ha^{-1} \cdot year^{-1}$. The higher positive influx of CO_2 of Caatinga in relation to the other land uses is due to its higher density of woody biomass.

As vegetation in the Caatinga-jatropha scheme becomes denser over time, its carbon stock and carbon sequestration capacity increases. However, to simplify this assessment, a constant rate of 0.8 $t \cdot ha^{-1} \cdot year^{-1}$ is assumed during the first 10 years, in which this landscape will be productive in terms of oilseed feedstock. Once the oilseed extraction becomes unfeasible both its carbon stock and storage capacity will continue to increase until reaching eventually the values of restored Caatinga, i.e. 14 t/ha and 2 $t \cdot ha^{-1} \cdot year^{-1}$.

A simple GHG balance was performed for each of the different land uses. This GHG balance considers the benefits related to the combustion of biodiesel, the biogas /bio-fertilizer from seedcakes and the methane emissions from cattle. While these elements cannot be considered as regulating ecosystem services, a balance of these GHG emissions of the land uses can add useful data to complement the ecosystem service (carbon sequestration) discussion.

To establish the overall GHG balances the combustion of biodiesel and biogas (compared to conventional diesel and LPG) is also considered. The combustion of 1 L of diesel generates 2.67 kg of CO_2 [116,117]. Each L of biodiesel B7 can save the emission of 0.11 kg CO_2 [118]. Furthermore the process results in the production of biogas with 60% methane content, which is equivalent to 0.877 L of LPG for each Nm^3 of biogas (the higher calorific values are 38 MJ/Nm^3 for methane and 26 MJ/L for LPG). The combustion of each L of LPG generates 1.77 kg of CO_2 [117,119,120]. To generate the same heat with biogas, it is necessary to burn 1.14 Nm^3 of that fuel which generates 1.54 kg of CO_2 [117]. Overall the use of biogas (instead of LPG) prevents the emission of 0.20 kg CO_2 for each Nm^3 of biogas combusted.

Finally this analysis also considers the GHG emission savings from the use of bio-fertilizer as a byproduct. This could save CO_2 emissions associated with the production of the equivalent synthetic fertilizer. The CO_2 footprint of an equivalent N-based chemical fertilizer was assumed to be 3.6 kg CO_2/kg [121]. Given the NPK content of the seedcakes, it was considered that 1 kg of chemical fertilizer is equivalent to 10.5 kg of castor and 19.2 kg of jatropha seed cake, respectively, as well as 66.7 kg of cow dung.

The GHG balances for each land use option are shown in Table 5. In particular, converting pastureland to ~~a~~ Caatinga-jatropha forest restoration could save annual emissions of 0.56 t of CO_2 and 0.11 t of CH_4 per hectare. Meanwhile, introducing a crop rotation scheme in single-crop farms could avoid annual emissions of 0.36 t of CO_2 per hectare.

4. Results and discussion

4.1. Ecosystem services trade-offs

Table 6 provides an overview of the ecosystem services provided by different land uses in the Northeast of Brazil. Based on the review of the literature (Sections 3.1.3, 3.2.3) some of these ecosystem services are quantified using secondary data, while others (especially supporting and cultural services) are assessed qualitatively.

Table 5
Products and GHG emissions for the different land uses.

	Caatinga natural vegetation	Local Jatropha varieties for forest restoration	Crop rotation scheme: castor and cowpea	Single-crop farmland (cowpea)	Pastureland
Carbon stock (direct measurements)	14 t·ha^{-1}	4 t·ha^{-1}	4 t·ha^{-1}	4 t·ha^{-1}	4 t·ha^{-1}
CO_2 flux (satellite and direct measurements)	2 ton·ha^{-1}·year^{-1}	0.8 ton·ha^{-1}·year^{-1}	0.4 ton·ha^{-1}·year^{-1}	0.4 ton·ha^{-1}·year^{-1}	0.4 ton·ha^{-1}·year^{-1}
Oilseed and fat yields	None	0.75 t·ha^{-1} (jatropha)	1.5 t·ha^{-1} (castor)	None	6 kg·ha^{-1} (tallow)
Biodiesel	None	225 L·ha^{-1}	634 L·ha^{-1}	None	5 L·ha^{-1}
Glycerol	None	30 kg·ha^{-1}	84.6 kg·ha^{-1}	None	1 kg·ha^{-1}
CO_2 emissions avoided (biodiesel)	None	24.7 kg·ha^{-1}	69.7 kg·ha^{-1}	None	0.5 kg·ha^{-1}
Waste seedcake	None	0.52 t·ha^{-1}	0.65 t·ha^{-1}	None	None
Biogas	None	78.7 Nm^3·ha^{-1}	96.7 Nm^3·ha^{-1}	None	None
CO_2 emissions avoided (biogas)	None	15.7 t·ha^{-1}	19.4 kg·ha^{-1}	None	None
CH_4 emissions (without biodigesters)	None	31.7 kg·ha^{-1}	39 kg·ha^{-1}	None	110 kg·ha^{-1}
CH_4 emissions (after biodigesters)	None	None	None	None	110 kg·ha^{-1}
NPK biofertilizer	None	15.7 kg N·ha^{-1} 3.6 kg P·ha^{-1} 7.8 kg K·ha^{-1}	41.9 kg N·ha^{-1} 12.9 kg P·ha^{-1} 6.3 kg K·ha^{-1}	None	11 kg N·ha^{-1} 7 kg P·ha^{-1} 9 kg K·ha^{-1}
CO_2 emissions avoided (biofertilizer)	None	98.2 kg·ha^{-1}	220 kg·ha^{-1}	None	1.5 kg/ha
TOTAL CO_2 balance (accumulation of CO_2 and emissions avoided)	2 Ton·ha^{-1}·year^{-1}	0.96 Ton·ha^{-1}·year^{-1}	0.76 Ton·ha^{-1}·year^{-1}	0.4 Ton·ha^{-1}·year^{-1}	0.4 Ton·ha^{-1}·year^{-1}
TOTAL CH_4 balance (emissions)	–	–	–	–	0.11 t·ha^{-1}·year^{-1}

Note: After the tenth year, the jatropha-forest restoration scheme can be considered as Caatinga.

Table 6 suggests that the different land uses considered in this paper produce different bundles of ecosystem services. The impact matrix below (Fig. 5), graphically illustrates the provision of these ecosystem services and co-benefits from the different land uses. Green shades depict positive service or co-benefit provision, blue shades no service/co-benefit provision, and red/orange shades negative service provision. The tone of the colour provides the intensity of the provision of service. For example, regarding the latter, strong red means a "highly negative" impact (e.g. high disservice) while light orange means a "low negative" impact (moderate disservice).

Table 6 and Fig. 5 suggest that the Caatinga forest provides numerous supporting, regulating and cultural services, and especially services that do not have a well-established market, e.g. water provision, soil regulation and GHG sequestration. On the other hand, Caatinga does not produce significant amounts of provisioning services for local communities besides timber and firewood, which are manifestly extracted unsustainably in the region (Section 1). However, Caatinga landscapes could provide revenues for small farmers, depending on initiatives that valorize this biome such as Payment for Ecosystem Services (PES) [122,123] or ecotourism [123,124], see below.

At the opposite end, pasture and cowpea mono-cropping in marginal soils can provide some provisioning services such as food and beef tallow (for biodiesel). On the other hand they have a negative impact on local water resources and in soil related services [42,92,114]. In the case of pasture, high amounts of methane are emitted to the atmo-

Table 6
Ecosystem services provision and co-benefits for alternative land uses.

Provisioning services and related co-benefits	Caatinga natural vegetation	Local Jatropha varieties for forest restoration	Crop rotation scheme: castor and cowpea	Single-crop farmland (cowpea)	Pastureland
Food	Low	None	8.7 GJ·ha^{-1}	16.2 GJ·ha^{-1}	1.7 GJ·ha^{-1}
Oilseeds for biodiesel	0 t·ha^{-1}	0.7 t·ha^{-1}	1.5 t·ha^{-1}	0 t·ha^{-1}	0 t·ha^{-1}
Beef tallow for biodiesel	0 t·ha^{-1}	0 t·ha^{-1}	0 t·ha^{-1}	0 t·ha^{-1}	6 kg·ha^{-1}
Energy from residual seedcake	0 GJ·ha^{-1}	1.8 GJ·ha^{-1}	2.2 GJ·ha^{-1}	0 GJ·ha^{-1}	0 GJ·ha^{-1}
Bio-fertilizer	None	15.7 kg N·ha^{-1} 3.6 kg P·ha^{-1} 7.8 kg K·ha^{-1}	41.9 kg N·ha^{-1} 12.9 kg P·ha^{-1} 6.3 kg K·ha^{-1}	None	11 kg N·ha^{-1} 7 kg P·ha^{-1} 9 kg K·ha^{-1}
Water provision	Positive (Very high)	Positive (Medium)	Negative (Medium)	Negative (Medium)	Negative (Low)
Regulating services					
CO_2 sequestration	14 t·ha^{-1}	4 t·ha^{-1}	4 t·ha^{-1}	4 t·ha^{-1}	4 t·ha^{-1}
Pest and disease control	Positive (Very high)	Positive (Medium)	Positive (Medium)	Negative (High)	None
Supporting services					
Soil services	Very high	High	Medium	Low	Low
Pollination	Very high	High	Very Low	Low	Low
Cultural services					
Aesthetic and recreational value	Very high	Low	None	None	None
Biodiversity					
Biodiversity	Very high	Medium	Low	Low	Low

Note: After the tenth year, the jatropha/forest scheme can be considered as Caatinga.

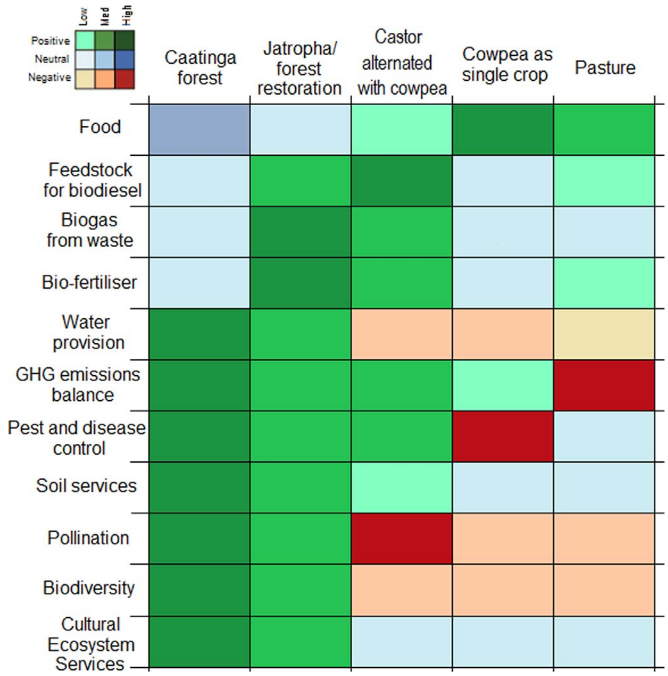

Fig. 5. Matrix of main ecosystem services impacts and co-benefits for the alternative land uses.

sphere (Table 5). These land uses also stand out for their low (or negative) provision of some supporting and regulating services, such as GHG sequestration and pest regulation.

Results suggest that the use of oilseed plants well adapted to the local climate can offer a mix of ecosystem services, both for the castor-cowpea rotation scheme and the Caatinga-jatropha forest restoration scheme. In sum, oilseed systems can provide a bundle of provisioning, regulating and supporting (in the case of the Caatinga- jatropha forest restoration scheme) ecosystem services (Fig. 5, Table 6), which in some cases can be much higher than the original land use (Fig. 6).

Both schemes provide feedstock for biodiesel production, and biogas from the residual oilseed cakes. Biogas production from local agro-industrial wastes can reduce the imports of LPG in the region and deforestation (for fuelwood) having thus multiple environmental benefits (Section 1). In this respect, it is noticeable that each hectare of Caatinga- jatropha forest restoration scheme could produce the equivalent to 276 L of LPG per year, while the castor-cowpea rotation schemes could produce a third of that amount. Another byproduct produced in the bio-digesters is slurry that can be used as a bio-fertilizer to increase soil nutrients and replace chemical fertilizers. Furthermore both schemes can provide some climate regulation services through the development of biofuel with positive GHG emission balances (Table 5) and increase in carbon stocks as in the case of the jatropha-forest restoration scheme.

4.2. Potential for scaling up

The two studied schemes can contribute to possibly boost the energy security and environmental sustainability targets of the Brazilian government. The castor-cowpea rotation scheme has the potential to be applied to 0.49 million ha where cowpea is cultivated as a single crop [28]. This land cover change, while it can reduce cowpea production, it could generate an added 0.3 billion L of biodiesel per year, enough to supply 7% of Brazil's biodiesel demand, diversifying from dominant feedstocks such as soybean and beef tallow (Section 1). The resulting castor seedcake could generate an additional 47 million of Nm^3 biogas. These energy gains can come with GHG emission savings of 0.2 million tons of CO_2. The effects on water availability and soil-related ecosystem services could be positive. However, as shown in the impact matrix (Fig. 5), pollination might be affected negatively.

The Caatinga-jatropha forest restoration scheme can contribute to Brazil's international commitment to recover 15 million ha of degraded pastures by 2020 [126]. In the Semi-arid region, where the productivity of pasture in marginal lands is low, a forest restoration scheme that uses native jatropha species can eventually reverse the land degradation associated with pastureland. This would be possible after a transition period of some years in which the land could produce oilseeds as the main provisioning ecosystem service. This alternative would entail some significant tradeoffs mainly associated with the loss of food production (beef). This land transition, however, could lead to an eventual increase in the provision of other provisioning services (e.g. feedstock for energy, water) as well as some regulating, supporting, and cultural services (Section 4.1).

When it comes to scaling up the Caatinga-forest restoration scheme, Northeast Brazil contains 33 million ha of pasture, of which 73% have exhibit a high level of degradation, only containing on average 0.4 heads of cattle per hectare [92]. Assuming that the Brazilian government decides to achieve its goal of recovering 15 million of those hectares through the studied Caatinga-jatropha scheme, it would imply the loss of land of 6 million heads of cattle, whose products produce annually 0.3 million tons of meat, 15 million L of biodiesel and 3 thousand tons of glycerol (from beef tallow). However the additional jatropha production could have important implications for the Brazilian biodiesel plan [4], as the country would temporary be able to receive an additional 3.37 billion L of biodiesel, which is almost enough to cover the entire current domestic demand [5]. The corresponding biogas production from jatropha waste seedcake could be as high as 1.2 billion Nm^3. This energy provision could have significant climate benefits due to the emissions saving of 8.4 million of tons of CO_2. Although these large numbers are just an example, the potential impact of this land use option in the energy market of the nation is clear.

4.3. Challenges and gaps

While both of the studied schemes exhibit some potential to improve ecosystem services provision from degraded pasturelands or cowpea monocultures (Section 4.2), there are two important challenges about their adoption. The first is the development of viable economic frameworks to make their exploitation attractive to small farmers, and the second is the development of the necessary scientific and agronomic knowledge to ascertain their long-term potential.

When it comes to the Caatinga-jatropha system, both local Government and cattle farmers are aware of the need of better land use management in the region. There is indeed a need to reforest headwaters and degraded lands in order to prevent desertification and secure water resources. In this context the Caatinga-jatropha forest restoration scheme can improve the delivery of regulating and supporting ecosystem services, combined with some level of feedstock production. However as discussed in Section 3.2.3, there is a lack of agronomic knowledge about the actual performance of such systems given the general lack of understanding of *J. curcas*[4] agronomy, let alone local jatropha varieties. While studies in the past decade have partially closed such gaps for local varieties in Brazil [9,10] the fact remains that there has been a global collapse of the *J. curcas* agroindustry [6,7]. This could discourage its adoption in Brazil, which lacks commercial experience in this agroindustry. However, on the plus side, there is a mature biodiesel market in Brazil which might reduce some of the production risks, as the lack of viable markets has been a major driver of jatropha collapse in across Africa [6,127].

[4] Jatropha curcas has been the jatropha species overwhelmingly used for biofuel production around the world.

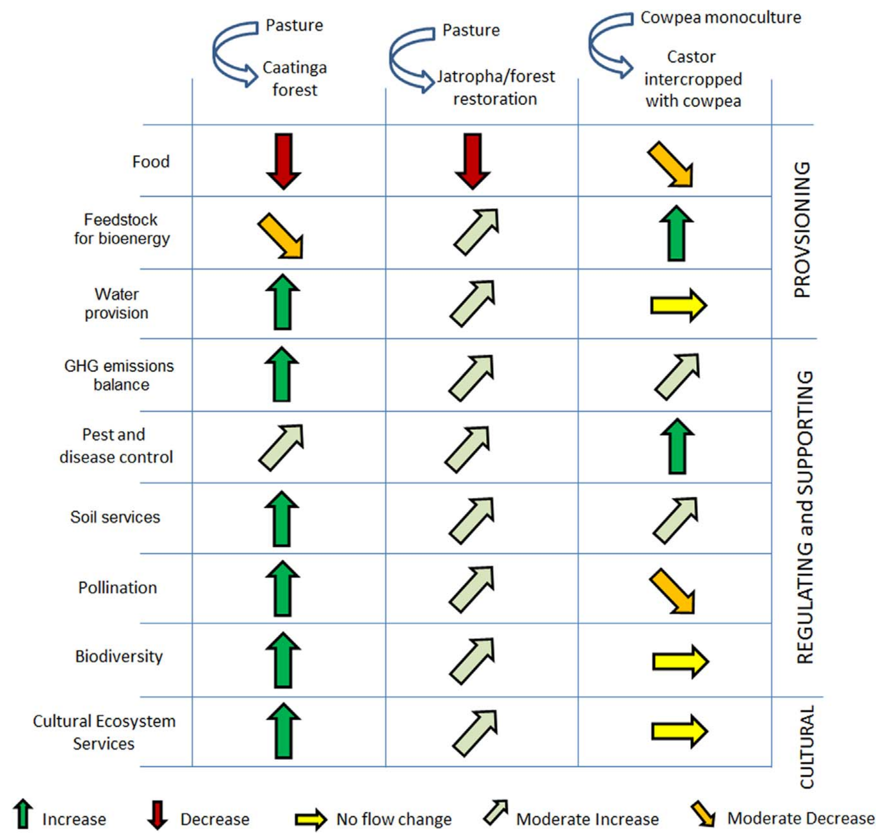

Fig. 6. Changes in the flow of ecosystem services due to landscape conversion.

When it comes to castor, its agronomy is much better understood, as the Northeast of Brazil is one of the main producing areas globally. In this case, it is economic competitiveness that can challenge its widespread adoption as a biodiesel crop, and especially the competition with soy. Soy has initiated a cycle of low prices as its supply nationally keeps growing while the Chinese demand has decreased (China is Brazil's greatest soy importer [128]). Biodiesel refineries will most likely continue to be a convenient destination for part of the soy harvest. At the same time, castor oil producers in the Semi-arid region will continue to find higher revenues by selling their harvest to the cosmetic and pharmaceutical industries (Section 3.1). Possible the higher prices for such castor oil uses will make uneconomical biodiesel production.

When it comes to castor, the plant's agronomy is much better understood in the Northeast of Brazil, as it is one of the main producing areas globally. In this case, it is the economic competitiveness that can challenge its widespread adoption as a biodiesel crop, and especially the competition with soy. Soy has initiated a cycle of low prices as its supply nationally keeps growing while the Chinese demand has decreased (China is Brazil's greatest soy importer). Biodiesel refineries will most likely continue to be a convenient destination for part of the soy harvest. At the same time, castor oil producers in the Semi-arid region will continue to find higher revenues by selling their harvest to the cosmetic and pharmaceutical industries. As a result the higher prices for such uses of castor oil will make uneconomical its use for biodiesel production.

The current situation is not expected to change both for jatropha and castor oil in the following years, until serious steps are taken by the Brazilian government to influence a shift towards their greater integration in biodiesel chains.

A key approach would be to integrate such schemes among the existing lines of government credits and incentives available to the Northeast region, and particularly the SCS Program ("Selo Combustível Social"). The biodiesel producers who participate in this program must buy 30% of its inputs from local family farmers and support them with technical assistance. In exchange, those biodiesel producers are recognized with the SCS standard and get tax incentives as well as better financial conditions from the Brazilian Development Bank (BNDES). Additionally, for those family farmers that aim to cultivate oilseed crops, there is an additional line of credit, within the Pronaf program (National Program for the Strengthening of Family Farming). The SCS has had significant success since its creation in 2005 as a complement policy to the Brazilian Program for the Production and Use of Biodiesel (PNPB). In the Northeast currently 3926 family farmers and 7 cooperatives have entered the biodiesel value chain [129]. Also, 4 out of the 6 existing biodiesel factories have been certificated with the SCS standard [129]. However these numbers are still lower compared to the rest of the country. For example in the rest of Brazil about 70,000 family farmers already participate as suppliers of the biodiesel industry while the biodiesel factories certified with the SCS are the overwhelming majority (80%) [129].

Another possibility is the development of biofuel-related Payment for Ecosystem Services (PES) schemes [130], such as those related to watershed protection in Brazil [131]. Local farmers could obtain revenues from castor and jatropha seeds in addition to the PES for offering pollination and/or watershed protection. However, first it is necessary to further strengthen the local biodiesel industry and establish an attractive PES framework. PES schemes have been a major focus of discussion in the new Brazilian Forest Code enacted in 2012. Since 2007 there have been several legislative proposals in the National Congress, however up to now none of those law proposals have concretized in the form of government credits. Our study can possibly provide a first step towards this direction as it offers as initial assessment of the ecosystem services trade-offs expected to manifest during the conversion of prevalent land uses in the Northeast (i.e. pasture and cowpea monoculture) for feedstock production. This study provides an advance from previous assessments of the region that focus exclusively on a monetary approach, such as the levelized cost of energy from available biomass sources [132].

However, in order to establish the trade-offs the present study is based on the analysis of secondary data collected from the literature. While such an approach can allow for a quick ecosystem services trade-off assessment, especially for systems that do not currently exist (e.g. Caatinga-jatropha forest restoration scheme), it has significant limitations similar to other methods commonly used for ecosystem services assessment such as benefit transfer, use of land cover proxies and simulation based on secondary data [133]. Firstly, reliance on secondary data collected from multiple sources, through different experimental settings, undertaken in different environmental contexts, often using different data collection/analysis protocols and quality criteria, inserts a significant element of uncertainty in the calculation [133,134]. Secondly there is significant subjectivity in some methodological decisions, particularly those pertaining to the qualitative assessment. An example from the present study is how expert judgment was used to visualize trade-offs related to pollination or cultural ecosystem services, which are particularly context-specific and for which not a lot of published material was available from the Northeast of Brazil.

To this end future research should be undertaken under real conditions to better understand both the bioenergy potential of these schemes in Northeast Brazil, as well as the nature and magnitude of the expected trade-offs. Extensive ecosystem services mapping exercises can help meet this gap in the literature [19,20], but validation will be equally important [133,134]. Future studies should also attempt to unravel the human wellbeing trade-offs of these proposals. Biofuel mediated change in ecosystem services provision can have important ramifications to human wellbeing that can be highly differentiated between different groups [21,135]. However concrete studies on these links are currently missing from the literature [18], as it is particularly challenging to link changes in the flow of ecosystem services to human wellbeing [136]. Understanding these linkages is equally important for establishing the true sustainability potential of these alternative feedstock systems for Northeast Brazil.

5. Conclusions

Based on the analysis of secondary data, both alternative biofuel systems that use oilseeds adapted to local climate can provide a bundle of provisioning, regulating and supporting ecosystem services. Feedstock for bioenergy is the most important ecosystem service derived from these multi-functional landscapes. In particular converting pasture to a jatropha-Caatinga forest restoration scheme could provide per hectare 0.7 t of oilseeds for biodiesel production and 1.8 GJ of usable energy, in the form of biogas from the residual seedcake. The castor-cowpea rotation scheme could provide per hectare 1.5 t of oilseeds for biodiesel production together with 2.2 GJ of usable biogas energy, per hectare. The per hectare carbon gains from the proposed biodiesel systems can be as high as 0.36–0.56 t of CO_2 per year (including use of biogas and bio-fertilizers).

However, some ecosystem services tradeoffs are expected if current agriculture/pasture landscapes are converted for feedstock production. The most obvious is that the loss of pastureland located in marginal areas can result in a modest but important loss of food, quantified as 100 kg of meat per hectare per year. When it comes to cowpea monocropping converted to a cowpea-castor rotation, a loss of 933 kg of food legume crop is expected per hectare per year. This loss of food could be offset by increased energy production and gains in biodiversity, pollination, water provision and soil-related services.

Adopting the studied schemes could have significant ramifications for the Brazilian biodiesel plan and, together with the biogas production from residual seedcakes, could have an overall positive effect on the energy security of the Semi-arid region of Brazil. However studies under real conditions should be undertaken in order to better understand both the bioenergy potential of these schemes in Northeast Brazil, as well as the nature and magnitude of the expected trade-offs.

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