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Socioeconomic and environmental assessment of biodiesel crops on family farming systems in Brazil

João Guilherme Dal Belo Leite [a,b,*], Flávio Barbosa Justino [b], João Vasco Silva [a], Madeleine J. Florin [a], Martin K. van Ittersum [a]

[a] Plant Production Systems, Wageningen University, P.O. Box 430, Wageningen 6700 AK, The Netherlands
[b] Departamento de Engenharia Agrícola, Universidade Federal de Viçosa, Av. P.H. Rolfs, s/n, Campus Universitário, Viçosa, MG CEP 36.570-000, Brazil

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ABSTRACT

In Brazil, local agricultural research agendas are increasingly challenged by the search for sustainable biodiesel crop options for family farmers, especially under semi-arid conditions. The aim of this paper is to explore the suitability of different biodiesel crops (i.e. soybean, castor bean and sunflower) through a set of environmental and socioeconomic indicators in a semi-arid (Montes Claros) and a more humid (Chapada Gaúcha) municipality in the state of Minas Gerais, southeast Brazil. A technical coefficient generator (TechnoGIN) was used to assess current (maize, beans, soybean and grass seed) and alternative (castor bean and sunflower) crops grown with current and alternative production techniques. The quantification of the inputs and outputs was based on farm surveys, expert knowledge, literature and field experiments. Although castor bean and sunflower are economically competitive with maize in Montes Claros, feed and labour requirements may hinder farmers' adoption. In Chapada Gaúcha, the double cropping system soybean/sunflower presented small economic gains when compared to soybean; it also increased nitrogen losses and biocide residues. We conclude that the scope for alternative and sustainable biodiesel crops on family farms is limited. Their economic benefits are small or absent, while their introduction can lead to higher environmental impacts and there may be trade-offs with food and feed availability at the farm level.

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1. Introduction

Worldwide, biofuels have become one of the most dynamic and rapidly growing sectors of the global energy economy (UN, 2007; Scragg, 2009; Tomes et al., 2010). There is increasing recognition that biofuel production can offer opportunities for countries to meet reduction of greenhouse gas emission targets, while empowering farmers through the generation of jobs and income in rural communities (Hazell and Pachauri, 2006; FAO, 2008).

Biofuel initiatives in Brazil have recently targeted biodiesel as a way of combining renewable energy production with rural poverty reduction. A national program for production and use of biodiesel was created in 2004 framed by a set of regulations based on mandatory blending of biodiesel with fossil diesel (Brasil, 2005). Expectations on further expansion of the mandatory blending policy, from the present 5%, led to a fast development of the biodiesel industrial production capacity which is able to supply two and a half times the current demand (Ubrabio, 2010; MME, 2012b). One of the main features of the policy is the inclusion of family farmers as feedstock suppliers to the biodiesel industry. Biodiesel producers who comply with feedstock supply from family farmers (Appendix S1) are granted a social fuel stamp, which implies tax exemptions and selling preference at biodiesel auctions (MDA, 2011).

Although the number of family farmers engaged in biodiesel crop production increased over the last five years, reaching over 100,000 families in 2010, biodiesel crop options are still narrow as 95% of the feedstock supplied is soybean. Soybean farmers are concentrated in the South and Central-West Brazilian regions; together they account for 91% of the feedstock supplied. The semi-arid Northeast region, on the other hand, has the highest concentration of family farms in the country (50%) and is responsible for only 5% of the total biodiesel feedstock acquisitions (MDA, 2011). Furthermore, this region has an agricultural GDP per capita that is seven times smaller than in the South and Central-West of Brazil (IBGE, 2006).

The Brazilian biodiesel policy is currently challenged by the search for alternative biodiesel crops that combine high oil productivity with better suitability for less endowed farmers, especially under semi-arid conditions. This strategy aims to increase oil production per area, thus positively affecting the energy balance of the production activity, and at the same time increasing family farms'

* Corresponding author. Tel.: +55 19 35211260; fax: +55 19 35211718.
E-mail address: dalbeloleite@yahoo.com.br (J.G. Dal Belo Leite).

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engagement. To be effective in engaging many family farms and increasing oil production in the near future (ca. 5 years), such crops should be compatible with the current farming systems (i.e. cropping sequence, labour and capital availability) plus well-established agronomic and management information for their cultivation should be available. Eligible biodiesel crops should then be assessed in combination with different production techniques and in terms of environmental and socioeconomic indicators. One way of improving knowledge regarding the complex relationship between agricultural production, environment and economy is through integrated quantitative methods and tools. These methods allow exploration of suitable production activities taking into account farmers' objectives, resource availability and technical feasibility (de Wit et al., 1980; Hengsdijk and van Ittersum, 2002). This would complement the existing literature assessing the feasibility of biodiesel production on family farms in Brazil, much of which is qualitative in nature (Abramovay and Magalhães, 2008; César and Batalha, 2010; Garcez and Vianna, 2009; Hall et al., 2011; Padula et al., 2012; Watanabe and Zylbersztajn, 2012). Such analysis is based on the description of production activities under specific biophysical and technological conditions in terms of inputs and outputs which are known as technical coefficients (Hengsdijk et al., 1999; Ponsioen et al., 2006). Inputs may include external nutrients, biocides and labour which together with the outputs can be expressed in their own physical units, and in monetary units. Besides crop production, outputs may include socioeconomic and environmental indicators such as labour use efficiency, cost–benefit ratios, nutrient losses and biocide residue (van Ittersum and Rabbinge, 1997). Moreover, although there are a number of studies that explore the agroecological potential of biodiesel crop options (Aranda-Rickert et al., 2011; Baldwin and Cossar, 2009; Dhyani et al., 2011; Zheljazkov et al., 2008), limited work has been done towards the integrated analysis of socioeconomic and environmental aspects of crop activities under different environmental conditions and technology levels. Finally, the importance of research that supports systematic analyses at more than one hierarchical level (e.g. field and farm level) cannot be understated (Volk and Ewert, 2011).

The objective of this paper is to explore current and alternative oil crops and their management through a set of environmental and socioeconomic indicators in two locations of Southeast Brazil. In this assessment, a semi-arid municipality, Montes Claros, and a more humid municipality, Chapada Gaúcha, of Minas Gerais state, were studied. Alternative production activities (biodiesel crops) and techniques were assessed against current – not so intensive in the use of machinery, biocide, and fertiliser – production techniques of maize (*Zea mays* L.) and beans (*Phaseolus vulgaris* L.) in Montes Claros and the more intensive production techniques of soybean (*Glycine max* L.) and grass seed (*Brachiaria* spp.) in Chapada Gaúcha. Findings from this analysis can produce useful knowledge for farmers and scientists on promising opportunities and major constraints of biodiesel crops under different production techniques. In addition, the outcomes of the assessment of different biodiesel crops under contrasting socioeconomic and agroecological conditions may help to provide insights for policy makers as to the overall evaluation of the biodiesel policy in Brazil. Finally, the proposed integrated analysis aims to generate a coherent field-level information package (technical coefficients) that will enable farm level studies (Leite et al., 2014b), thus contributing to further insights into the effects of biodiesel crop cultivation when farmers' resources (land, labour, capital) and objectives (i.e. profit maximisation, food self-sufficiency) are taken into account. Although this study focuses on the assessment of indicators that are relevant to the uptake of biodiesel crops by family farmers, we acknowledge there are other important indicators, such as GHG emissions and net energy production, when it comes to the overall sustainability evaluation of biofuel production.

In this study the selected methodological approach and technical coefficient generator are generic and can also be applied to other regions.

2. Materials and methods

The description of key terminology used in this study is summarised in Table 1.

2.1. Modelling approach

The exploration of agroecological and socioeconomic sustainability of current and alternative production activities requires a comprehensive compilation of their inputs and outputs. It means that all inputs (i.e. labour, biocides, fertilisers and input costs) and outputs (i.e. yield levels and nutrient losses) associated with a particular crop with a specific production technique and land unit have to be quantified. A comprehensive database was built based on information on current and alternative production activities from which different production activities can be assessed through the various possible combinations of crops, production techniques and land units. To generate such combinations and calculate the inputs and outputs a computer program (TechnoGIN) was used. TechnoGIN (Ponsioen et al., 2006) is a technical coefficient generator which allows for the quantification of inputs and outputs of a large number of current and alternative production activities. Although TechnoGIN was first developed for Ilocos Norte, Philippines (Ponsioen et al., 2003), it has recently been re-designed as a more generic and flexible tool for further applications in other regions of Asia and Africa (Patil et al., 2014; Reidsma et al., 2012; Wolf et al., 2004).

The input and output coefficients of current production activities in TechnoGIN are based on survey data. Alternative production activities, however, are quantified based on knowledge of the biophysical processes of plant and animal production, technical recommendations and land use related objectives following the so called design criteria (Hengsdijk and van Ittersum, 2002). For these activities, target yields were based on crop models (potential and water limited yields), field crop experiments (rain fed and irrigated), expert knowledge and literature. Inputs were determined using the so called target-oriented approach, i.e., seeking the technically optimum combination of inputs to realise the target yield level (van Ittersum and Rabbinge, 1997).

Table 1
Summary of the terminology used in the quantification of crop activities.

Terminology	Description
Production level	Level of primary output per unit area
Land unit	Relatively homogenous area in terms of landscape, soil characteristics and climate conditions
Production technique	A set of agronomic inputs required to realise a particular output level
Production activity	Crop or crop rotation cultivated on a particular land unit and characterised by a specific production technique
Current production activity	Production activity characterised by actual farmers' management in terms of crop choices and technology adoption
Alternative production activity	Production activities technically feasible but not yet widely applied by farmers
Target oriented approach	Technical optimal combination of inputs to realise a particular output level or production level
Technical coefficients	Input and output coefficients of a production activity

Source: van Ittersum and Rabbinge (1997) and Hengsdijk et al. (1999).

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Table 2
Farm types' characteristics.

Characteristics	Unit	Farm type 1	Farm type 2	Farm type 4	Farm type 5
Farm area	ha	116.7	46.4	2.4	49.1
Annual crops	ha	81.5	1.8	0.8	49.1
Graze crops	ha	3.7	29.1	0.8	0.0
Crops	-	Soybean, grass seed	Maize, beans	Maize, beans	Soybean, grass seed
Soil/landscape	-	Ferralsols, arenosols/plains	Ferralsols, nitosols/plains	Ferralsols, nitosols/plains	Ferralsols, arenosols/plains
Land tenure	-	Owned	Owned	Sharecropped	Rented
Municipality	-	Chapada Gaúcha	Montes Claros	Montes Claros	Chapada Gaúcha

2.2. Case study area

Minas Gerais is the largest state in the Southeast region of Brazil, with an area of 586,520 km^2 (Fig. 1A). In this area different climatic conditions can be found, from semi-arid to humid, where also a wide variety of agroecological zones and a broad array of family farm types occur. The north of the state is a transition from the Cerrado (savannah) towards semiarid, being one of the poorest regions of the state (Fontes et al., 2009). The north-west of the state, which is on the frontier of the Brazilian Central-West, is one of the most important crop producing regions, accounting for ca. 38% of the state's soybean production (SEAMG, 2012).

Within each region one municipality was selected for this study, i.e., Montes Claros in the north and Chapada Gaúcha in the north-west (Fig. 1A). The criteria used to select these two municipalities were a high concentration of family farms, active biodiesel initiatives and suitable agroecological conditions for biodiesel crops (MAPA, 2012). Chapada Gaúcha is located at 15°17′S and 45°37′W, 725 km from the state capital Belo Horizonte. The tropical semi-humid climate, with 4–5 dry months, is characterised by average air temperatures above 18 °C and average annual rainfall of 1286 mm. Montes Claros is located more centrally at 16°44′S and 43°51′W, 425 km from the capital. In this municipality tropical semi-arid condition can be found, with at least 6 dry months. The average temperature is above 18 °C and annual rainfall amounts to 1050 mm. Savannah (Cerrado) is the predominant vegetation in both municipalities. Furthermore, there are also differences in soil and landscape characteristics between both municipalities.

Three different landscape features were selected from a soil and landscape database (UFV et al., 2010) to characterise land units within the municipalities: (i) soil fertility level: low (≤50% of base saturation) or moderate (>50% base saturation); (ii) soil type (FAO); and (iii) landscape topography (steepness): plain (≤8%), plain-hilly (8–20%) or hilly (20–45%). From the selected criteria nine different combinations can be derived, four occurring in Chapada Gaúcha and five in Montes Claros (Fig. 1B,C).

In Chapada Gaúcha, the low-fertile ferralsols with plain landscape are dominant (Fig. 1B). This landscape combined with the use of fertiliser and lime favours large scale mechanised production activities such as soybean and grass seed, which combined account for 82% of the cropped area (IBGE, 2010).

Montes Claros has more diverse soil types with a more hilly landscape (Fig. 1C). In this region, shallow and rocky soils are common, thus making agriculture more difficult. Less mechanised, small-scale crop cultivation (plains) and extensive cattle production (hills) are the most important production activities. In this municipality maize and beans account for 78% of the cropped area (IBGE, 2010).

Table 3
Design criteria and their variants for identifying production activities.

Design criteria	Variants
Land unit	Two: plain (ferralsols + nitosols), plain (ferralsols + arenosols)
Crop options	Eight: maize, beans, castor bean, spring sunflower, soybean, grass seed, summer sunflower (soybean/sunflower)
Production technique	Four: current, best farmers' technical means, improved, irrigated
Yield levels	Four: current, best farmers, water limited, potential

2.3. Data collection

A farm survey was performed in all district zones in both Montes Claros ($n = 10$) and Chapada Gaúcha ($n = 2$) from 2010 to 2012. The survey was performed in two steps. First 555 farmers were interviewed with respect to their production activities, crop management, outputs, resource endowment (land, labour and capital), access to inputs, market orientation and collective action. From this database a farm typology was developed with the support of principal component and cluster analysis (Leite et al., 2013). Five farm types were identified, from which four were selected to be explored in this study (Table 2). Mixed farmers (Farm type 3) in Montes Claros and Chapada Gaúcha refers to horticulture producers. This group of farmers is not prioritised by the biodiesel policy because of the low economic competitiveness of biodiesel crops compared with locally marketed vegetables. Hence, this farm type was not explored in this study.

A second survey was performed covering 80 farmers in the two municipalities, accounting for the main production activities previously identified in the farm typology. Village leaders and extension agents assisted with the identification of concentration domains of a given farm type within each village, where farmers were then randomly selected. A total of 35 soybean/grass seed farmers (Farm type 1: $n = 20$; Farm type 5: $n = 15$) in Chapada Gaúcha and 45 maize/beans farmers (Farm type 2: $n = 20$; Farm type 4: $n = 25$) in Montes Claros were interviewed.

The second survey was used to derive the technical coefficients of each production activity including the quantification of all inputs required to achieve a certain output under the current production techniques. Data on crop area, yields, labour and management, input use and costs, and output prices for an average year were collected. This database was also complemented with soil analysis ($n = 64$, 2009–2011), soil profile information (Radambrasil, 1986) and weather data (1979–2009) (INMET, 2012) at municipality level.

2.4. Design process: current and alternative production activities

2.4.1. Land units and crop options

Main *current* production activities were identified in each of the research areas through farm surveys (previous section). *Alternative* production activities were specified according to biophysical possibilities and their technical feasibility combined with land use-related objectives (Hengsdijk and van Ittersum, 2002).

The intensive soil tillage management associated with current production activities in Chapada Gaúcha (grass seed) and Montes Claros (maize and beans) limited crop production to plain areas. As no alternative soil management is explored in the present study, and to account for potential soil loss from steeper parts of the landscape, alternative production activities were also restricted to plain areas (Table 3). Based on the farm survey and expert knowledge,

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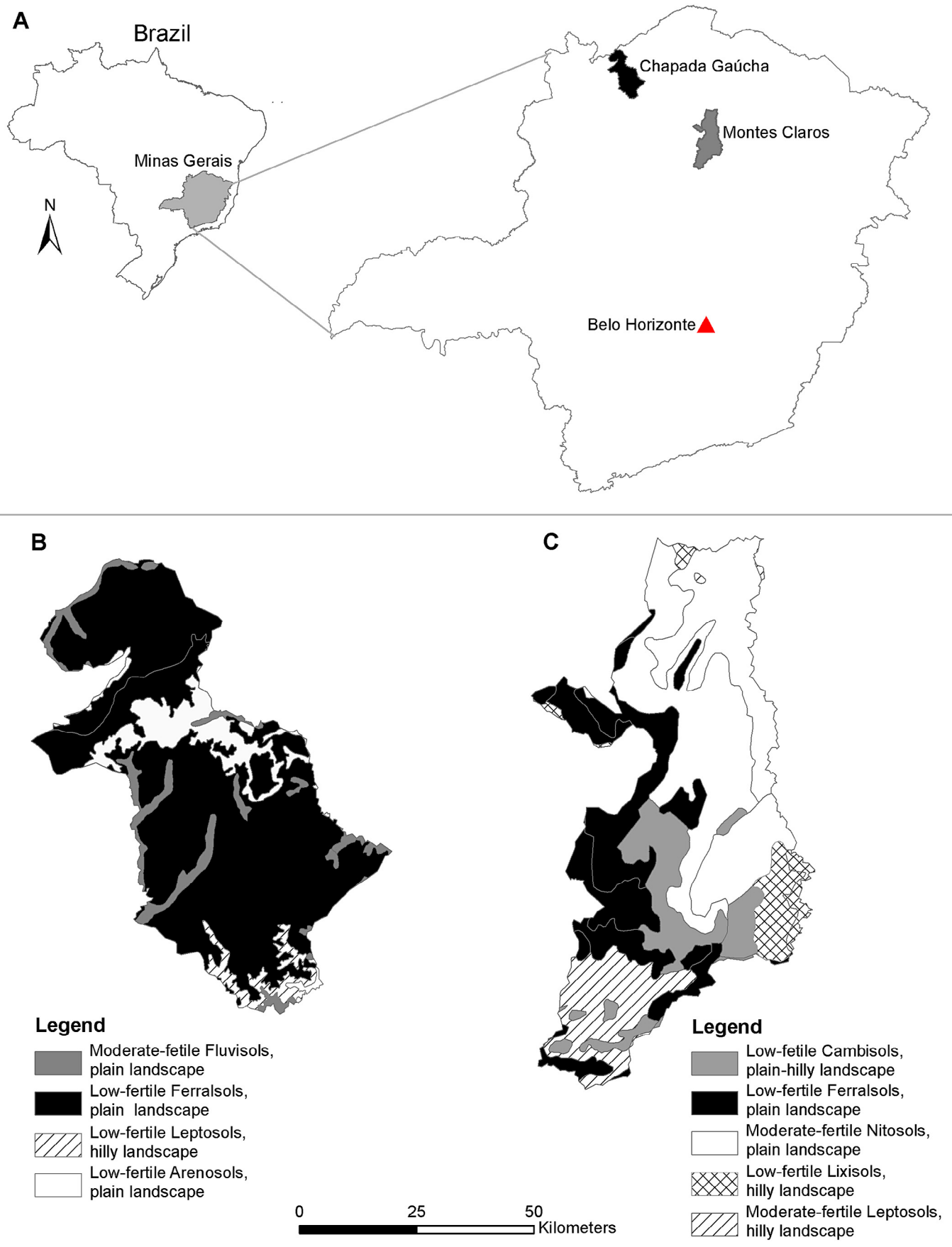

Fig. 1. Map of Brazil with the State of Minas Gerais, its capital and research municipalities (A); soil and landscape features of Chapada Gaúcha (B) and Montes Claros (C).

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Table 4
Relative change (%) of production activities characteristics under different production techniques (*current, best farmers, improved and irrigated*) and land units (Chapada Gaúcha and Montes Claros). Positive (+), negative (–) or neutral (0) changes are calculated as percentages of current values (100).

Production activity characteristics	Montes Claros				Chapada Gaúcha			
	Current	Best farmers	Improved	Irrigated	Current	Best farmers	Improved	Irrigated
Yield levels	Low	Best farmers	Water-limited	Potential	Low	Best farmers	Water-limited	Potential
Fertiliser recovery fraction	na	100	+10	+10	100	0	+10	+10
Biocide use	na	100	–10	–10	100	+20	–10	–10
Fuel use	na	100	0	0	100	+20	+100	+100
Labour requirements – crop management	100	–80	–42	–42	100	+100	+200	+200

na, not applied.

we concluded that the differences in soil types within each land unit did not have significant impact on yield levels of current and alternative production activities. We argue this is justified because (1) the relatively low variation in soil types associated with similar geology (parent material) in plain areas, and (2) a fairly homogeneous fertiliser use in both research regions, i.e. a very low use of fertilisers in Montes Claros resulting in major nutrient limitations which override the influence of soil fauna, and a relatively high use of fertiliser in Chapada Gaúcha resulting in very limited variation in yield levels across the region. We therefore considered one soil type per municipality.

We assumed that crop options should be compatible with current farm infrastructure, thus not requesting further adaptation investments (e.g. new equipment), due to the short time horizon of the analysis (ca. 5 years). Moreover, there must be a fairly established research and development (R&D) agenda around novel crops, i.e. literature, technical assistance, experimental data and seed availability, thus ensuring relatively reliable information to be used under different production techniques (NAE, 2005; MAPA, 2012). Although oil crops such as macaúba palm (*Acrocomia aculeata* Mart.), sesame (*Sesamum indicum* L.) and jatropha (*Jatropha curcas* L.) show some promise in the region, lack of technical information (i.e. crop yield levels, management and production costs) and technology on crop production still constrains its introduction among farmers (Junqueira, 2011; Sousa et al., 2011; Embrapa, 2012b). Main crop options considered to have an established R&D agenda, thus enabling capacity building, are peanut (*Arachis hypogaea* L.), cotton (*Gossypium hirsutum* L.), sunflower (*Helianthus annuus* L.) and castor bean (*Ricinus communis* L.) (de Castro and Lima, 2011). Cotton and peanut would imply major adaptations by farmers in terms of investments in farm equipment associated with crop management and harvest, plus storage infrastructure, market and agronomic information. As a result, castor bean and sunflower were selected to be explored as alternative crops. Sunflower was explored as a single crop (spring sunflower) in both Chapada Gaúcha and Montes Claros (Table 2). A double cropping system with soybean followed by summer sunflower was explored only in Chapada Gaúcha (soybean/sunflower – Table 3) where the rainy season is longer (November to April). In general, single cropping systems are most common, especially in Montes Claros where the wet period is about 150 days (November to March). Castor bean was considered suitable only in Montes Claros where family manual labour for crop harvest was available, as this crop still lacks appropriate machines.

2.4.2. Production techniques and yield levels

Different production techniques were also explored, i.e. current and alternative techniques (*best farmers' technical means, improved management* and *irrigated*) (Table 3). Alternative production techniques were based on near future possibilities (ca. 5 years), thus incorporating technologies available to farmers. This implies that management and use of inputs following technical recommendations are already available or in the R&D pipeline but not yet widely applied. Based on the less input intensive production activities in Montes Claros and the highly mechanised and intensive ones in Chapada Gaúcha, production techniques were designed to explore the effects of both intensification and a more rational use of inputs. Yield levels associated with different production techniques were defined based on farm surveys (*current, best farmers'*), water-limited and potential crop model simulations, field experiments and expert knowledge (*improved, irrigated*) (Table 3).

Current production techniques were defined based on farm surveys and represent the average combination of inputs. *Best farmers' production technique* represents ca. 5% of the surveyed farmers and accounts for a more input-intensive production system, i.e., higher levels of fertiliser, seed technology, biocides and machinery, leading to higher yield levels compared with the *current* production technique (Table 4). The *improved management* technique assumes a more rational use of inputs. A precision agriculture approach is incorporated in which the required inputs for crop growth and protection are met without deficiency or excess (Cassman, 1999), implying high efficiency in the use of nutrients and biocides. Nitrogen fertiliser recovery fraction was increased by 10% assuming an improved management based on a better synchrony between crop N demand and the N supply throughout the growing season (split fertiliser applications) when compared to *current* and *best farmers'* technical means (Cassman et al., 2002; Kang, 2009). Different fertiliser types were not considered due to the still limited access by farmers and the widespread use of urea as the primary source of N supply (farm survey). In this technique, biocide use was reduced also by 10% due to a better spraying management combined with a pest/disease monitoring system (Table 4). The improved *irrigated* production technique was developed from the *improved management* considering available irrigation equipment on some farms. It was also defined using the target-oriented approach with improved yield levels and input use (Table 4).

Farmers' cultural characteristics, which may affect crop preferences, collective action engagement and use of inputs with further impacts on yield levels (César and Batalha, 2010; Watanabe and Zylbersztajn, 2012), were not systemically explored in this paper. However, the consequences of cultural aspects are, to a certain extent, embodied in the current production techniques and crop options considered in this study as these reflect farmers' choices and access to inputs such as fertilisers and biocides. More detailed information as to the cultural and other aspects of farmers in Montes Claros and Chapada Gaúcha and biodiesel crops, particularly castor bean, can be found in Leite et al. (2013).

2.5. Quantification of production activities using TechnoGIN

TechnoGIN calculates a series of input–output relationships which can be used in a resource use efficiency analysis. It is a Microsoft Excel based program where the calculation rules are programmed in Microsoft Visual Basic. There are three main types of technical coefficients which can be generated: (i) input requirements in

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physical and economic terms, i.e. fertiliser, biocide, seed, labour, and costs; (ii) physical production, mainly referring to crop yield; (iii) environmental impacts, i.e., biocide use, water requirement and nutrient balances (Ponsioen et al., 2006). In this study socioeconomic (crop production, labour requirements and gross margins) and environmental (nutrient balance and biocide use) indicators were assessed.

2.5.1. Target yields

Yield levels (water-limited and potential) set for alternative production techniques in each land use type were defined in TechnoGIN mainly using crop growth models built into the Decision Support System for Agro-Technology (DSSAT) (IBSNAT, 1993; Jones et al., 2003). Previous studies which calibrated and tested DSSAT in the State of Minas Gerais for soybean (Rodrigues et al., 2013), beans (Oliveira et al., 2012) and maize (Costa et al., 2009; Pereira et al., 2010) were used to perform further simulations for Chapada Gaúcha and Montes Claros. Simulated yields, from 1979 to 2009, were averaged and used to set target yield levels in TechnoGIN.

A different approach for estimating yield levels was used for castor bean, grass seed and sunflower. For these crops, modelling efforts and literature are scarce. Yield levels for castor bean were defined based on expert knowledge from extension services in the north of Minas Gerais under rainfed (farmers' experience) and irrigated conditions (field experiments). A similar approach was used to attain grass seed yield levels. Extension agents from a soybean/grass seed cooperative in Chapada Gaúcha were interviewed together with farmers to explore crop yields under different production techniques. For sunflower, the crop model OILCROP-SUN, which had been tested in Brazil (Rolim et al., 2001), was used to simulate yields during spring (single cropping systems) and summer (double cropping system). To calibrate OILCROP_SUN an experiment was carried out in Viçosa, Minas Gerais, while a series of 27 experiments from different Brazilian locations in the states of Minas Gerais, Goiás, Distrito Federal, São Paulo and Paraná were used for model validation (Appendix S2). Sunflower yields were simulated (1979–2009) for different sowing dates with a weekly time step from August 25th to March 30th, accounting for spring (Montes Claros and Chapada Gaúcha) and summer (Chapada Gaúcha) sowing periods.

2.5.2. Nutrient balances

Nutrient balances (N, P and K) were calculated in kilograms per hectare, for each production activity, based on the incoming (fertiliser, manure, symbiotic bacteria and mineralisation) and outgoing (crop uptake and nutrient losses) flows of nutrients. Crop nutrient uptake is calculated using the QUEFTS model (Janssen et al., 1990) integrated with TechnoGIN. In QUEFTS nutrient uptake is calculated assuming a balanced supply of N, P and K defined by the crop yield level and nutrient concentrations in crop residues and harvestable products (Nijhof, 1987). Nutrient losses due to leaching, denitrification, volatilisation and fixation are calculated as a share of the nutrient inputs which are assessed based on soil and weather conditions, i.e. soil texture, aerobic/anaerobic conditions and precipitation (Cantarella, 2007; Ernani et al., 2007; Novais et al., 2007). Nutrient balances for current production activities are calculated based on current yields and fertiliser rates (farm survey) and calculated nutrient losses. Alternative production activities use a similar method, but nutrient inputs are calculated using the target-oriented approach which is defined by target yield levels and estimated nutrient losses (Ponsioen et al., 2003).

To evaluate QUEFTS, the current fertility status of soils, assessed through soil analysis, was used to calculate nutrient inputs following literature recommendations. These values were then compared with those calculated by the QUEFTS model (Table 5). The statistical analysis indicates that the built-in nutrient balance component performs well in estimating nutrient inputs when compared to soil analysis recommendations. This also provides a good basis for reliable estimations of nutrient rates of alternative production activities.

Table 5
Nitrogen (N), phosphorus (P) and potassium (K) inputs in kg ha^{-1} according to soil analysis (current recommendation) and TechnoGIN (calculated), and the statistical indicators for model performance across the six crops.

Crops	N (kg ha^{-1})		P (kg ha^{-1})		K (kg ha^{-1})	
	Current	Calculated	Current	Calculated	Current	Calculated
Maize	60	54	26	33	37	33
Beans	50	44	13	11	17	21
Castor	60	48	17	18	25	23
Sunflower	80	89	39	45	58	63
Soybean	15	10	48	50	75	76
Grass seed	38	37	35	31	33	28
Statistics ($n = 6$)						
RMSE[a]		14.8		14.0		10.1
ME[b]		0.9		0.9		1.0

[a] RMSE = root mean square error (Appendix S2).
[b] ME = modelling efficiency (Appendix S2).

2.5.3. Water balance and biocide residue index (BRI)

The water balance is an important model component used to estimate irrigation requirements of alternative production activities. It was calculated per period of 10 days based on water inflows (precipitation, irrigation) and losses, which consist of actual evapotranspiration (ET), calculated by the multiplication of crop coefficients and reference ET. Reference ET is calculated using the Penman–Monteith equations (Allen et al., 1998) and long term daily weather data (1979–2009) (INMET, 2012). Furthermore, soil water content is limited by the soil water holding capacity defined by soil texture. When the balance is negative in a certain period (10 days) there is a water shortage, which could be supplemented with irrigation.

Biocide residue index (BRI) is defined by the use of biocides (kg of active ingredient ha^{-1}), toxicity index and soil persistence characteristics. It is used as an environmental risk indicator associated with biocide use and calculated as: BRI = [biocide (kg ha^{-1}) × active ingredient fraction (kg kg^{-1}) × toxicity index × persistence index active] ÷ 100. Values below 100 are considered to be safe, between 100 and 200 permissible and above 200 unsafe (Vasisht et al., 2007).

2.5.4. Labour requirements and gross margin

Labour requirements are defined for each production activity and include labour for land preparation, crop establishment, management and harvest. Labour demands were specified in labour days (8 hours) per hectare in Montes Claros (manual labour) and hours per hectare in Chapada Gaúcha (mechanised labour).

Gross margin was also calculated for each production activity and was defined by crop income derived from crop yields and prices, minus the costs of all variable inputs such as hired labour, machinery, fertiliser, biocides, seeds and fuel. The information related to costs (fertiliser, biocides, etc.) and crop prices was obtained from the farm survey as representative for an average year (current production activities) and literature (alternative production activity) in which a five year average (2007 to 2011) was used (CONAB, 2012; IEA, 2012). The exchange rate used (US$ 1.00 = R$ 1.75) was based on an average of daily values from March 2011 to July 2012 (BCB, 2012).

2.6. Sensitivity analysis of crop prices

A sensitivity analysis was performed for prices of the alternative crop options under the *current* production technique to explore

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to what extent changes could impact the economic attractiveness (gross margins) of biodiesel crops against current ones. This analysis was limited to crop prices based on three main criteria: (i) the database mainly includes biophysical inputs (i.e. fertiliser, biocides, seeds, labour requirements and fuel) which have limited annual variation and are tightly associated with farmers' management; (ii) yield levels of different crops are often correlated with climate related events, e.g. drought, hail, floods, affect all crops; (iii) crop prices showed to be a relevant component of gross margins (ca. 31% – farm survey) which are likely to vary, due to local, regional or global factors, regardless of farmers' management. Gross margins of biodiesel crops under *current management* were explored through the stepwise (plus or minus 5%) increase of crop prices and compared against current crop options in Montes Claros and Chapada Gaúcha.

3. Results

3.1. Crop yields and gross margins

Crop yields associated with *current* and *alternative* production techniques differ in the two land units. Yield gaps, i.e., the difference between potential (*irrigated*), and *current* yield levels are relatively large in Montes Claros where *current* production activities are managed under low input and technology use (machinery, seeds, fertiliser and biocides) than in Chapada Gaúcha (Fig. 2A,B). As a result, when comparing *current* with *best farmers*, yield levels increase on average by 200% in Montes Claros and 68% in Chapada Gaúcha.

Water supply in the *irrigated* production technique positively affects yield levels in both locations (Fig. 2A,B). There is an average yield increase of 110% in Montes Claros and 75% in Chapada Gaúcha from the *best farmers* to the *irrigated* production technique. Despite the significant impact on crop yields, irrigation adoption does not always lead to proportional economic benefits. Costs associated with water supply, mainly energy, outweighed gains from crop yields leading to a decrease in economic returns (Fig. 2C,D). Beans is the only crop for which irrigation seems to be a reasonable economic choice (Fig. 2C). There are two main reasons for this, i.e., the high price of beans, and the relative short beans cycle (90–110 days) leading to less water demand, about 370 mm ha^{-1} which is relatively small when compared to castor demanding 640 mm ha^{-1} (ca. 180 days crop cycle) and the double cropping systems soybean/sunflower, demanding 970 mm ha^{-1}.

Gross margins associated with alternative crops, i.e., castor beans and sunflower, in Montes Claros show higher economic gains when compared with maize under current and alternative production

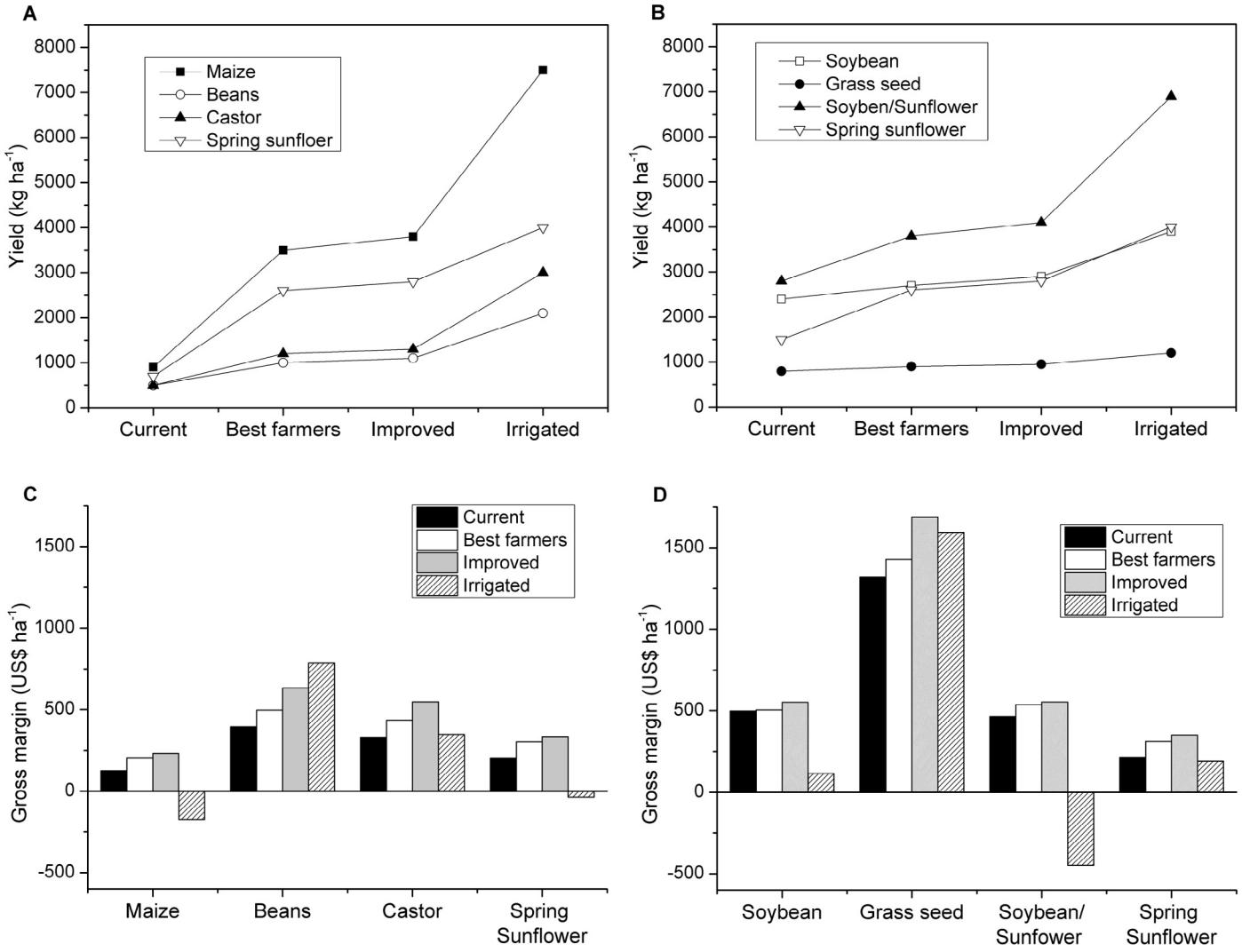

Fig. 2. Yield levels (A and B), gross margins (C and D) for current and alternative production activities with different production techniques in Montes Claros (A and C) and Chapada Gaúcha (B and D).

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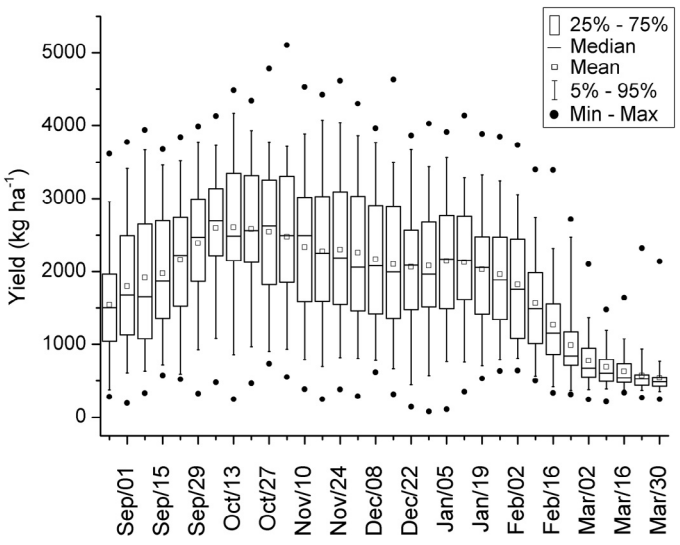

Fig. 3. Box-plot of the simulated sunflower yields from 1979 to 2009 under rainfed conditions in Chapada Gaúcha with different sowing dates.

techniques (Fig. 2C). Besides being the most economically attractive crop, beans contribute substantially to family food subsistence and only production surpluses are sold in local markets. This is also the case for maize which is used as animal feed. In Chapada Gaúcha, alternative production activities, i.e., spring and summer sunflower (soybean/sunflower), present minor economic gains compared to soybean and grass seed (Fig. 2D). Spring sunflower is not a competitive crop option, unless the *best farmers'* production technique is used, and when sown during summer in rotation with soybean (soybean/sunflower), it yielded higher gross margins (6%) than soybean monoculture. This economic gain, however, relies on short cycle (90–110 days) soybean varieties which allow sunflower to be sown in the second half of February when crop yields can still reach 1000 kg ha^{-1} (Fig. 3). Sunflower yield levels drop considerably with sowing dates from January 19th onwards, mainly due to water shortage associated with the end of the rain period (Fig. 3).

The sensitivity analysis based on crop gross margins under *current* production technique show that prices of castor bean and sunflower would have to increase by ca. 17% and 74%, respectively, to become economically competitive with beans in Montes Claros (Fig. 4A). In Chapada Gaúcha summer sunflower prices cultivated after soybean (soybean/sunflower) would have to increase by 20%, whereas in a single cropping system (spring sunflower) prices would have to increase by ca. 57% (Fig. 4B).

3.2. Labour requirements

Labour requirements differ substantially between both municipalities. Mechanised production activities in Chapada Gaúcha show a progressive increase in labour demands from *current* to *irrigated* production techniques (Fig. 5B). This is caused by the intensification of biocide use (number of sprays) in *best farmer's means* management, pest and disease monitoring strategies in *improved* and labour associated with *irrigation* practices. Grass seed, however, shows limited labour response to alternative production techniques relative to other production activities in Chapada Gaúcha. This is because 70% of labour requirements of grass seed are associated with crop harvest, which is not affected by alternative production techniques.

In Montes Claros, where current production activities are based primarily on family manual labour, there is a decrease in labour demands from *current* to alternative production techniques (Fig. 5A). From *current* to *best farmers' means*, labour requirements decrease by more than half. This results from the substitution of manual labour for land preparation (hired machinery) and weeding activities (biocide use). Castor bean shows the greatest difference in labour between current and alternative production techniques as its longer cycle (210 days) is associated with higher labour requirements for weed control (Fig. 5A). For all production activities there is an increase in labour demand from *best farmers' means* to *irrigated* production technique which is related to pest and disease monitoring and manual weeding (*improved*), and water supply management (*irrigated*).

3.3. Biocide residues and nitrogen losses

Results from the selected environmental indicators show a consistent increase in nitrogen losses and biocide residues with the intensification of production activities in both research locations (Fig. 6). Chapada Gaúcha shows higher levels for the selected

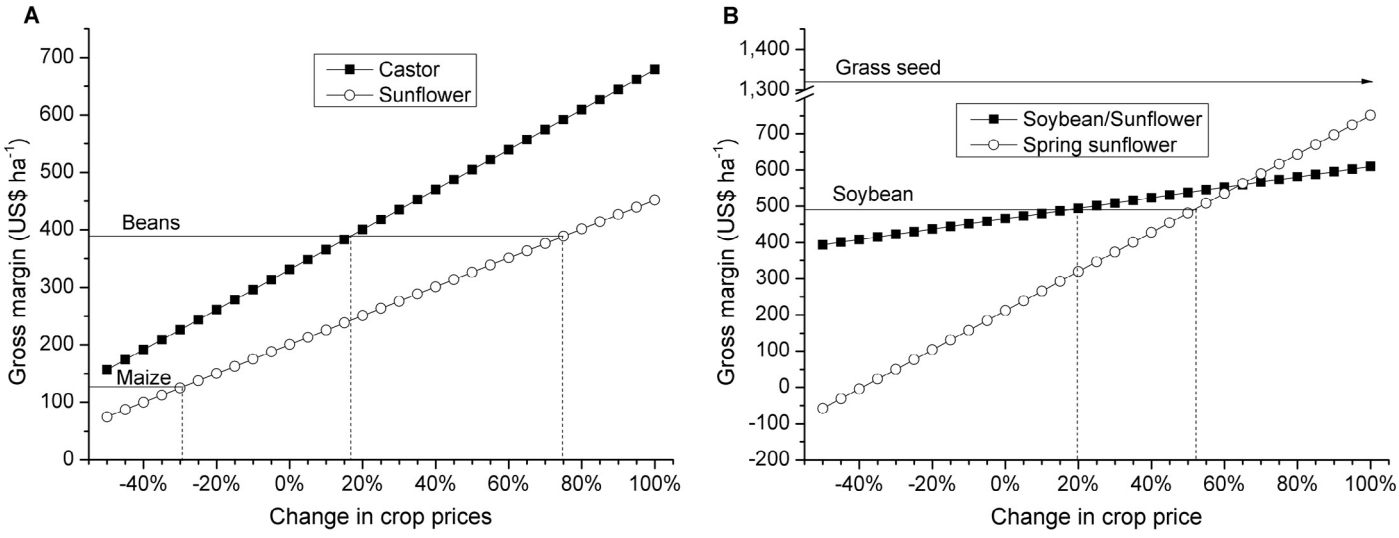

Fig. 4. Sensitivity analysis of gross margins based on the increase (steps of plus or minus 5%) of crop prices of alternative production activities in Montes Claros (A) and Chapada Gaúcha (B).

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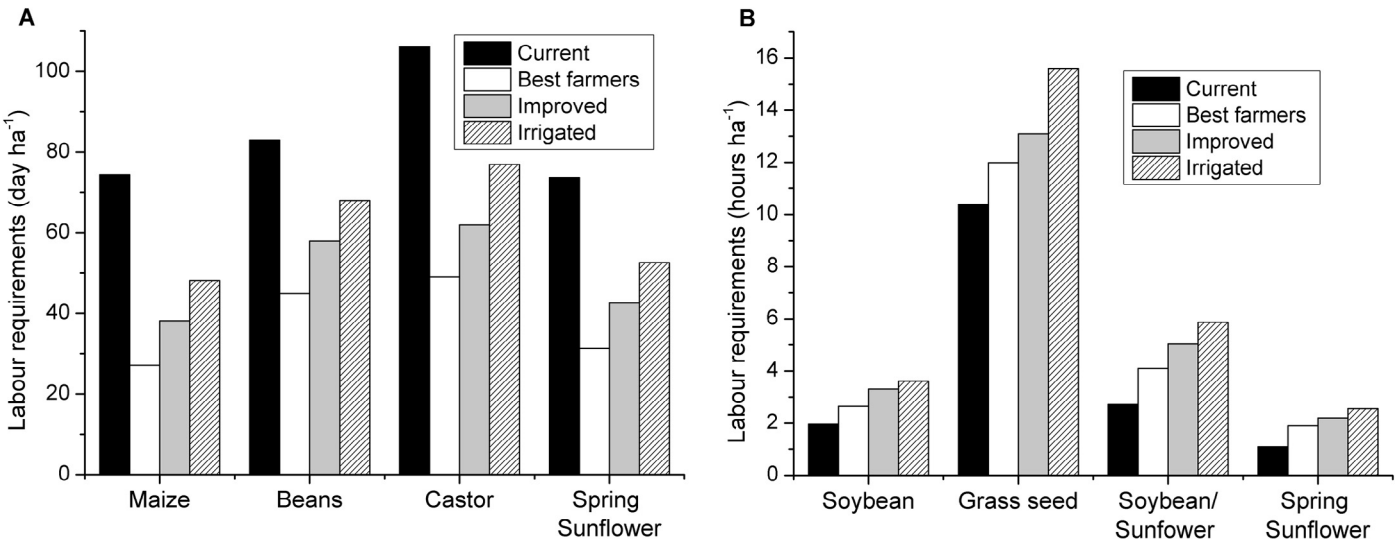

Fig. 5. Labour requirements for current and alternative production activities with different production techniques in Montes Claros (A) and Chapada Gaúcha (B).

environmental indicators than Montes Claros for all production techniques. *Best farmers'* management presents higher values of biocide residue index (BRI) than other production techniques in both municipalities. Unsafe values of BRI are associated with soybean/sunflower, grass seed and maize. A more rational use of biocides (*improved*) is effective for most of the crops, with BRI values brought to permissible levels ($100 \leq BRI \leq 200$) (Fig. 6A,B). The soybean/sunflower rotation, despite the lower BRI values under *improved* management, remains an unsafe production activity.

Nitrogen losses are affected mainly by the rate and management of fertilisers. For most of the crops there is an increase in nitrogen losses from *current* to *best farmers' means* (Fig. 6C,D). Soybean, however, shows no increase in losses because of the similar nitrogen fertiliser rates in all production techniques (Fig. 6D). The *improved* management of fertiliser based on the split N applications decreases N losses relative to *best farmers' means*. Such decrease, however, is less evident for spring sunflower and maize (Fig. 6C,D). These crops require higher rates of fertiliser under *improved* management due to higher yield levels (Fig. 2A,B). The close relation between nitrogen losses and yield levels results in the highest N losses per ha for *irrigated* production activities. This is associated with nitrogen requirements calculated to satisfy potential crop yield demands. The double cropping system soybean/sunflower results in the highest losses of nitrogen from all production activities, amounting to 73 kg ha^{-1} under *irrigated* management (Fig. 6D).

4. Discussion

4.1. Socio-economic indicators

Although biodiesel crops have been promoted among farmers as a way of boosting farm income (MDA, 2011), the results indicate that the economic benefits of such activities are not evident. Gross margins for the selected production activities show that in Montes Claros the highest economic returns come from beans, which is also an important subsistence crop (just as maize). Although not as profitable as beans, maize plays a key role as a fodder crop supporting animal production activities in all identified farm types in Montes Claros. Among the biodiesel crops in this region castor bean is economically more attractive than sunflower. However, the integration of oil and feed production, which is regarded as an important enabling component of castor bean production in the north of Minas Gerais (Silva Jr. et al., 2012), is limited due to its toxicity and the lack of safe and economically feasible detoxification methods (Severino, 2005). Moreover, castor bean labour requirements (mainly associated with weeding and harvest) are ca. 38% higher than from maize, beans and sunflower (Fig. 5A). This increases the competition for land with current crops as labour is constrained among family farmers in the region (Finco and Doppler, 2011; Florin et al., 2012).

Intensification strategies are regarded as an effective way of dealing with resource related constraints (e.g. labour) associated with small scale farming systems (de Ridder et al., 2004; Dixon et al., 2001). For the selected crop activities in Montes Claros, the combination of mechanised equipment for land preparation, fertiliser use and biocide use lead to an improvement in yield levels of about 200% with 70% reduction in labour requirements from *current* to *best farmers' means* (Fig. 5A). This could allow farmers to engage in biodiesel crop production, e.g. castor bean, without compromising current food and feed demands. However, cash constraints coupled with limited access to credit and inputs (fertiliser, machinery, seeds, etc.) often undermine farmers' ability to invest in higher input farming systems (Tittonell and Giller, 2013).

Sunflower, although less profitable than castor bean, has been acknowledged as a promising biodiesel crop (Ribeiro and Carvalho, 2006). Low labour requirements (similar to maize) and its potential to combine oil and feed (i.e. cake after oil extraction) led to the inclusion of sunflower in the most recent R&D agendas, particularly focused on semi-arid regions (MME, 2012a).

In Chapada Gaúcha, sunflower gross margins, when cultivated during the spring as a single crop, are considerably lower than that of current crops (soybean and grass seed) under both current and alternative production techniques (Fig. 2D). The double cropping system soybean/sunflower presents minor economic benefits compared with single soybean. This shows that the addition of a summer crop (sunflower) does not result in substantial economic gains as revenues from sunflower are almost completely absorbed by its production costs. Furthermore, this double cropping system can only be a feasible option when farmers use short cycle soybean varieties allowing sunflower to be sown late in February before yield levels drop below 1000 kg ha^{-1} (Fig. 3).

Economic gains of alternative production activities based on major changes in crop prices seem an unlikely scenario (Fig. 4A,B). Moreover, in the last decade crop prices have been fairly stable, except for two peaks of castor and bean prices (Fig. 7). Therefore, market driven changes capable of shifting the economic competitiveness

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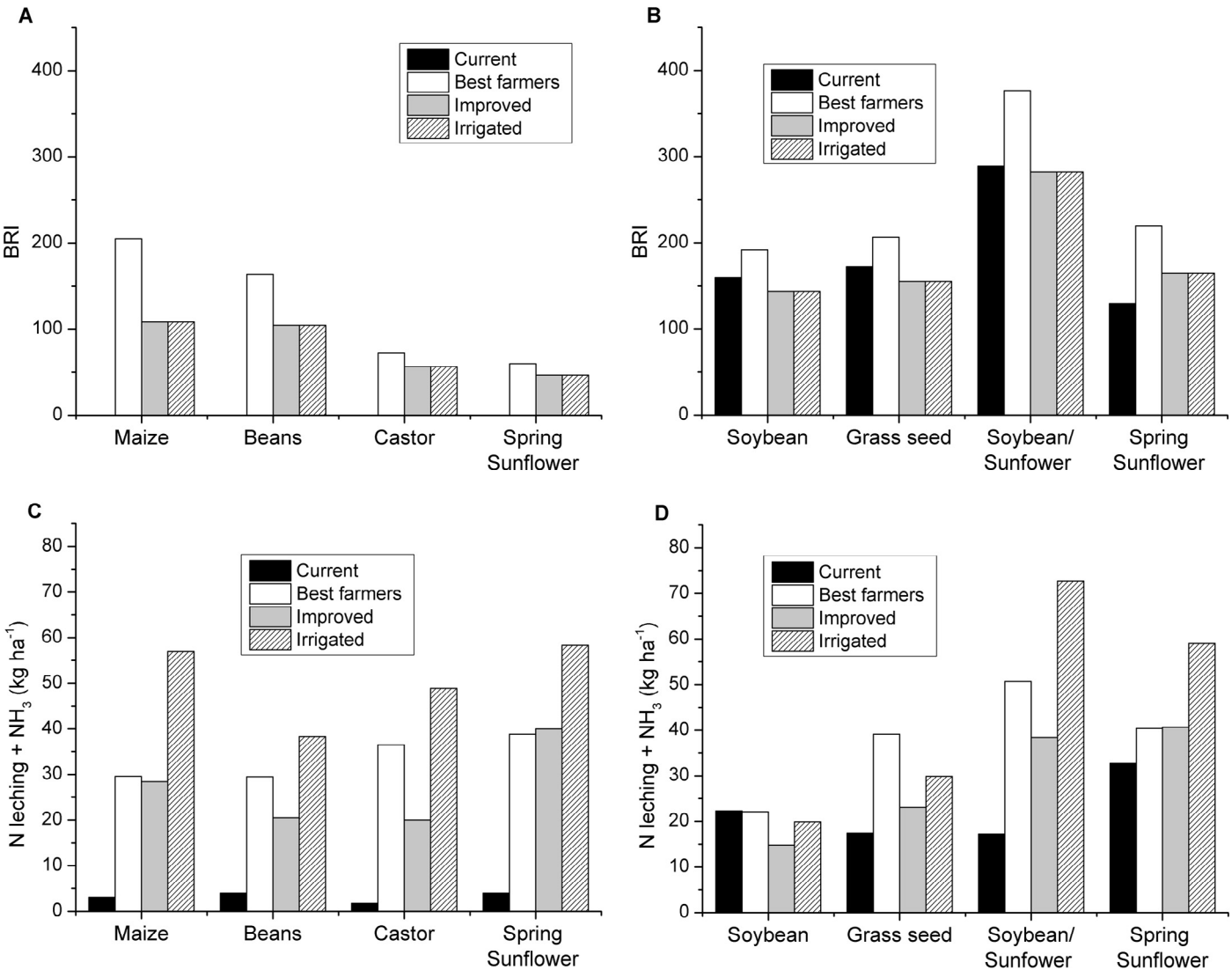

Fig. 6. Biocide residue index – BRI (A and B) and nitrogen losses (C and D) for current and alternative production activities with different production techniques in Montes Claros (A and C) and Chapada Gaúcha (B and D).

of current and alternative production activities does not seem likely.

4.2. Environmental indicators

Agricultural intensification has been recognised as a way to address the increasing concerns on global food security (Cassman, 1999; Tittonell and Giller, 2013; van Ittersum et al., 2013). The provision of food, fibre and bioenergy from agricultural systems, which are essential for human well-being, can also be the source of environmental impacts, including loss of wildlife habitat, water pollution and biocide poisoning (Power, 2010).

In both research areas, nitrogen losses increase from *current* to *alternative* production techniques (Fig. 6C,D). This increase in losses is particularly high for production activities in Montes Claros, where no fertiliser is used under *current* crop management (Fig. 6C). Such losses, however, come with gains in crop production. This can lead to higher nitrogen use efficiency (NUE) from the applied N inputs, by reducing the amount of N losses from organic and inorganic N pools, when compared to monoculture activities (Cassman et al., 2002; Raun and Johnson, 1999). The ratio between yield levels and

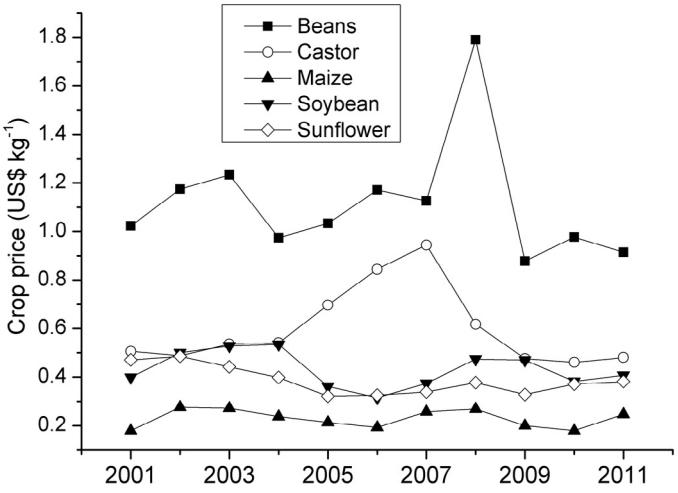

Fig. 7. Annual crop prices from 2001 to 2011. Source: (CONAB, 2011; IEA, 2012). Crop prices were updated on the basis of the consumer national price index (INPC: www.ibge.gov.br).

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N losses (yield kg ha^{-1} ÷ N losses kg ha^{-1}) is on average 23% higher for soybean/sunflower than the summed individual values of spring sunflower and soybean monocultures. It means that N losses per kilogram of grain are reduced by 23% if sunflower follows soybean, instead of being cultivated in the spring. Anderson et al. (1997) found that double cropping activities can be an effective way of reducing N losses from soil profiles, thus reducing the potential environmental contamination.

In Brazil, high nitrogen losses are mainly caused by volatilisation of ammonia (NH_3) which is mainly affected by agroecological conditions and the surface application of urea fertiliser (Cantarella et al., 2001; Lara Cabezas et al., 2008; Lara Cabezass and Souza, 2008; Vitti, 2003). Although improving synchrony between N supply and crop demand (split N applications) with *improved* management (Fig. 6C,D) prove to be an efficient way of limiting N losses; further gains in NUE could be achieved using slow release fertilisers, i.e. nitrate N instead of urea. Cantarella et al. (2003) found nitrogen volatilisation losses of up to 44% with urea compared to 2% losses with the use of ammonium nitrate fertilisers. Despite being effective, the popularity of such fertilisers remains low among farmers due to the costs (Shaviv, 2005), which in Brazil can be up to 100% higher than urea (CONAB, 2012).

From the energy perspective, there is an overall understanding that a double cropping system of soybean followed by sunflower is opportunistic, as it allows the increase of oil production without compromising current soybean areas (Ribeiro and Carvalho, 2006). However, environmental impacts of biocide use in this production activity are often overlooked. Farmers commonly adopt spray strategies based on combining multiple biocides (pesticides, fungicides and herbicides) as a way to save labour and prevent pest/disease outbreaks. This management leads to the use of less specific biocides which affect non-target species, e.g. natural enemies. Results from the BRI show that, despite the implementation of a more rational management and use of biocides (*improved* production technique), unsafe values of BRI can still occur with the soybean/sunflower rotation (Fig. 6B). An important reason for the high values of BRI could be the monocropping of soybean for the last 30 years in Chapada Gaúcha. Crop diversification, although a way to reduce pest infestations (Krupinsky et al., 2002), is limited for economic reasons. Moreover, there are pests common to soybean and sunflower (Moscardi et al., 2005) which could jeopardise positive effects of introducing another crop in the rotation.

The implementation of soybean integrated pest management (IPM), which was first introduced in Brazil in the 1970s, is likely to be the most effective strategy to reduce biocide residues (Gazzoni, 1994; Moscardi et al., 2009; Oliveira et al., 1988; Panizzi, 2006). Soybean fields in the south of Brazil showed that pesticide use can be reduced by 50% to 78% through pest monitoring, combined with biological control, and minimal use of non-persistent and pest specific biocides (Corrêa-Ferreira et al., 2010; Kogan et al., 1977). However, the limited availability of commercial biological agents and the lack of pest resistant varieties coupled with farmers' constraints in knowledge and trained labour still hamper further development of IPM (Hoffmann-Campo et al., 2000; Kogan, 1998).

5. Conclusion

The results obtained in this study indicate that, although it has been claimed that biodiesel crops are able to enhance rural income, such economic gains are not evident when systematically compared with current crops such as beans (Montes Claros), and soybean and grass seed (Chapada Gaúcha) under different production techniques. Sunflower and castor bean are economically competitive with maize in Montes Claros where current production activities are less input intensive. Feed requirements and labour availability seem to be important determinants of farmers' choice when biodiesel crop production is considered. In this region, intensification strategies (alternative production techniques) can be a way of dealing with labour limitations and increasing gross margins and yield levels. However, cash constrains coupled with limited access to credit and inputs must be overcome.

In Chapada Gaúcha the double crop rotation soybean/sunflower is economically competitive only with the *best farmers' means* production technique, although with limited increases in gross margins when compared to soybean monoculture. Moreover, there are also environmental drawbacks associated with this double cropping activity. *Improved* management proved to be effective in limiting nitrogen losses. On the other hand, a more balanced use of biocides seemed not sufficient to reduce the level of biocide residues.

The selected model-based approach using TechnoGIN was useful in assessing an array of activities in terms of socio-economic and environmental aspects of the investigated production activities. It also provided insights into the impact of alternative production techniques available in the R&D pipeline but not widely adopted by farmers. The resulting quantitative assessment can inform farmers and support the policy making process as it sheds light on the opportunities and limitations of biodiesel crops under the different socioeconomic and agroecological contexts of family farmers in Montes Claros and Chapada Gaúcha. Although policy recommendations were explored more comprehensively in previous works (Leite et al., 2013, 2014a), in this assessment the overall benefit of well-known biodiesel crops, particularly in less intensive production systems (i.e. farmers in Montes Claros), appeared to be limited. This suggests that changes to the targeted crops and/or policies (e.g. bonus prices, subsidies, etc.) is necessary. In a companion paper (Leite et al., 2014b), the technical coefficients reported here were employed in a bio-economic model that incorporates farmers' resources (e.g. farm size, capital and labour) and objectives (profit and/or self-sufficiency). This allowed the exploration of alternative policy scenarios (subsidies, bonus prices, tax incentives) in which distinct conclusions and recommendations were drawn for the identified farm types in the research areas (Leite et al., 2014b).

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Appendix: Supplementary material

Supplementary data to this article can be found online at doi:10.1016/j.agsy.2014.10.005.

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