What are the impacts of sugarcane production on ecosystem services? A Review

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Abstract

Since the 1950s sugarcane production has grown rapidly from less than 0.5 billion tonnes in the late 50s to reach over 1.9 billion tonnes in 2012 on about 27 million hectares of agricultural land. This expansion has been boosted by the high demand for bioethanol promoted as a sustainable bioenergy source which accounted in 2010 for the biggest share of the global biofuel market.

Despite its benefits, the scientific debate on sugar is growing especially that counterarguments are so many, including negative impacts on different interacting ecosystems and human well-being, e.g. bigger stress on land and water resources, environmental externalities on air, a harmful impact on the biodiversity and endemic species, negative environmental externalities, health, and socio-economic aspects. This paper provides a narrative systematic review (SR) of the impacts of sugarcane production on these different ecosystems employing the ecosystem services framework for its acceptance by policy-makers.

The references included for the SR were 163 and results showed that the majority of the studies are from Brazil, Australia, South Africa and the USA (= 75% of the literature), most of
them were from peer-reviewed journals (85%), and most of the case studies adopted a quantitative research approach (93%).

The literature assessed showed that sugarcane, like all agro-systems, depends on the practices and techniques to transform negative impacts into positive externalities on ecosystems and human well-being. However, the literature studied failed to include the inter-linkage in sugarcane production impacts’ and therefore to evaluate the related ecosystem services with respect to the Millennium Ecosystem Assessment (MA) framework to account for existing trade-offs. Therefore, the findings are addressed to the scientific community and decision-maker for an intensification of interdisciplinary and integrated research based on the MA framework to cover all ecosystem services, for sustainable development of the sugarcane sector.

Keywords
Sugarcane, impacts, ecosystem services, human well-being, agro-systems, sustainability

1. Introduction

Sugarcane is a perennial grass belonging to the genus Saccharum L. and comprising six different species (D’Hont et al., 1998). It is indigenous to the warm temperate to tropical climates of South and Southeast Asia, although it is now grown in more than 100 different countries around the world (FAO, 2019). The world production grew from just below 448 million tonnes harvested on around 8.9 million hectares in 1961 to reach over 1.9 billion tonnes on about 27 million hectares. While Brazil has been for years now the world producer of sugarcane (39.0% of world production in 2017), with impressive expansion rates observed every year, India is the second biggest world producer, 15.7% of world’s production (Table 1), Guatemala and Peru had respectively the highest sugarcane productivity at around 121 t ha\(^{-1}\) (FAO, 2019).

This expansion has been accompanied with a growing demand for foodstuffs, animal feed, and industry, but the major driver of this rapid increase has been the demand for bioethanol, promoted as a sustainable bioenergy source as it offers a high energy balance and high GHG reduction (Lisboa et al., 2011; FAO, 2008; Zuurbier and Van de Vooren, 2008; Goldemberg,
2007); it reduces uncertainty associated with prices volatility of fossil fuel (Black et al., 2012; Zuurbier and Van de Vooren 2008) giving at the same time a secured source of income for farmers boosting thus rural development (Swinnen and Squicciarini, 2012; Sexton and Zilberman, 2008); and it did not show to have a major impact on global food prices (Baffes and Dennis, 2013).

Despite the benefits of sugarcane mentioned above the scientific debate is growing (Goldemberg et al., 2008), especially that counterarguments are so many, including impact on different ecosystems\(^1\), and environmental and socio-economic aspects (Ridley et al., 2012), and according to Millennium Ecosystem Assessment (2005), the change of ecosystems would impact “provision services” by these and human well-being would be modified. The main impacts found in the literature are as follows:

- The growing competition between sugarcane and food crops on land-use is threatening world food production already facing the challenge of feeding 9 billion people by 2030. The impacts of this competition are described to be devastating for food security (Harvey and Pilgrim, 2011; Rajagopal, 2007).
- Land use and in particular land-use change could participate in the increase of GHG emissions when a farmer replaces a forest or switches from food crop production (less emitter) to sugarcane (direct land-use change). Consequently, a direct land-use change, some other farmers would have to change the type of production or replace a natural area into productive land to fulfil the market need of the crop directly replaced. This has been defined in the literature as indirect land-use changes (ILUC) (Andrade de Sá et al., 2013; Adami et al., 2012; Lapola et al., 2010; Searchinger et al., 2008).
- A harmful impact on the biodiversity and endemic species as a result of land-use change and the expansion of ILUC especially on behalf of the Amazon forest in Brazil the world largest sugarcane producer e.g. ecosystem disequilibrium leading to the dominance of some predators (Verdade et al., 2012; Bernard et al., 2011).

\(^{1}\) An ecosystem is “a dynamic complex of plant, animal, and microorganism communities and the non-living environment interacting as a functional unit” (Millennium Ecosystem Assessment, 2005). The inter-linkage of these natural ecosystems has always provided services the human beings who became dependent on them to maintain their living, these are called ecosystem services.
• Negative environmental externalities e.g. air quality and GHG emissions due to sugarcane burning, nutrients depletion, and related acidification and eutrophication potentials on soil pollution and erosion (Hein and Leemans, 2012; Verdade et al., 2012; Botha and von Blottnitz, 2006).

• Bigger stress on water resources due to changes in irrigation needs (Thornton et al., 2009; Smit and Singels, 2006; Everingham et al., 2002), especially in countries where water is already a constraint for agriculture such as South Africa where water withdrawal for sugarcane production is 9.8% of the total irrigation withdrawal. Water quality deterioration is a direct consequence of water exploitation increase by water pollution from agronomic and agro-processing practices in different countries (Chandiposha, 2013; Gerbens-Leenes et al., 2012; De Fraiture et al., 2008; Smeets et al., 2008; Zuurbier and Van de Vooren, 2008).

• Social impacts related to farmers health and well-being due to diseases transmitted through some predators (De Andrade et al., 2011; Silva et al., 2010), working conditions, land rights, worker rights, forced and child labour (Ridley et al., 2012; German et al., 2011; Smeets et al., 2008) and economic impacts related to costs of production and labour conditions (Goldemberg et al., 2008).

The impacts of sugarcane production on these ecosystem services and the well-being of people have not been systematically approached in the literature even though the methodology has been highlighted recently in scientific studies on biofuels and other agricultural systems (e.g. Gasparatos et al., 2011) and the interactions (benefits/impacts) have been distinguished on different scales (local level, national level, and global level), at which decision-making could take place (UN-Energy, 2010; Stromberg et al., 2009). Therefore, we need a robust and transparent scientific evidence for global policy development for sugarcane production.

Even though ecosystem services associated with sugarcane agro-systems have been assessed for the first time in Australia in 2005 (Park et al., 2008; Thorburn et al., 2005), the literature presents no evidence on the adoption of ecosystem services framework in their research methodologies. Consequently, the major objective of this research is to assess the impacts of sugarcane expansion on the ecosystem services and the impacts on human well-being.
employing the ecosystem services framework adopted by the Millennium Ecosystem Assessment (MA) and discuss it in the broader context of sustainable agriculture. The outcome is a synthesis of scientific evidence for different level stakeholders and decision-makers accounting for the trade-offs generated from the interrelation of these different ecosystems as suggested by the MA for sustainable sugarcane production. We adopted for this purpose an evidence-based highly structured approach, the Systematic Review (SR) known for the rigorous scientific conclusions it draws for science and decision making, reducing the susceptibility to bias (CEE, 2018).

2. Materials and methods

We adopted in this paper the SR methodology as described in the systematic review guidelines (CEE, 2018). This approach includes setting the question of the research; drafting the protocol; conducting a systematic search tailored to the question; article screening; critical appraisal and data extraction to examine any bias susceptibility, and; data synthesis (CEE, 2018).

The primary question is maybe the most important aspect in the systematic review, its formulation is a task that requires the participation of all the actors. The compromise in defining the question is between taking a holistic approach and adopting a reductionist one (Pullin et al., 2009). Ecosystem services are all the natural systems that people use to extract benefits and to increase their well-being and this includes water, land, air, biodiversity, diseases and cultural services (Fisher et al., 2009; Hassan et al., 2005). Therefore, the primary research question that would cover all the aspects of sugarcane production and the related counterarguments described above would be:

“What are the impacts of sugarcane production on ecosystem services?”

The research question is broken down as required by the CEE guidelines into definable elements known as the PICO/PECO: i) the population (Sugarcane production from 1950 onwards because world yearly data for sugarcane are collected and published since 1950 by the United Nations Food and Agriculture Organization (FAO, 2019; Zuurbier and Van de Vooren, 2008) and sugarcane consumption for bioethanol production began in the late forties
in Brazil (Kovarik, 2008), without any location restriction; 

ii) interventions (The intervention is the expansion of sugarcane production since the seventies of the last century leading agricultural, environmental and social changes); 

iii) comparators (Impacts and/or benefits of this expansion on different ecosystem services. Under sugarcane/different land uses); 

iv) outcomes (defined as quantitative/qualitative changes in water, changes in soil and land use/land change, changes in air quality, changes in level of biodiversity, environment, changes in food availability and social aspects).

Different database sources have been identified to be used in the review including scientific and grey literature, but only literature published in English was considered. As for the grey literature, web-based engines have been used (google.com, googlescholar.com, dogpile.com and other organisations’ websites), we only considered a maximum of 50 ‘hits’ which are the most relevant. We exported all the retrieved references into Mendeley software before the use of inclusion criteria for relevance assessment.

All literature retrieved in the first step have been subject to relevance screening using inclusion criteria, which included 

i) relevant subjects (Any country, any scale, crop: sugarcane); 

ii) type of intervention (Increase in sugarcane productivity, expansion of sugarcane production); 

iii) comparator (Compares benefits and/or impacts on ecosystem outcomes); 

iv) Methods (experiments and/or modelling); 

v) outcomes (Studies that consider benefits/impacts on water, land and air resources, biodiversity, wildlife, environment, food, health, income and other social aspects (e.g. labour rights, child labour)).

A first filtering process has been undertaken, based on the title of the database; a second filter followed, it was based on the abstracts’. The remaining literature underwent a full-text review. All data considered relevant (Based on inclusion criteria and the ‘outcome’), has been selected and tabulated using MS Excel spreadsheets. The extraction has been cautiously documented, and any reasons for data heterogeneity have been reported for transparency.

We adopted a narrative synthesis approach to explain the results because we believe it is more suited in our case, where the subject content is broad with a wide range of potential outcomes. Furthermore, the narrative approach has the potential to highlight knowledge gaps and areas for targeting for decision making.
3. Results

The systematic review results are divided into different stages as summarised in Figure 1.

The literature retrieved consisted of 2,626. Duplicates were removed leaving in total 2,200 records for the following step. The first screening reduced the number to 649 followed another screening based on the abstract which led to a total of 336 references (Figure 1), divided between countries, type of ecosystem services and year of publication.

The review included case studies from 24 different countries (Figure 2) including Argentina, Australia, Belize, Brazil, China, Costa Rica, El Salvador, Fiji, India, Iran, Kenya, Malawi, Mozambique, Mauritius, Mexico, New Guinea, Nicaragua, Philippines, South Africa, Swaziland, Taiwan, Thailand, the USA, and Zambia. However, many of the studies are from Brazil, Australia, South Africa and the USA (Table 2).

Most of the references gathered were from peer-reviewed journals (85%), while the literature from the grey literature did not exceed 15% including books and book chapters (2%), proceedings papers (6%), reports (6%), and thesis (1%); and most of the case studies adopted a quantitative research approach (93%) however qualitative and mixed approaches has also been assessed (6% adopted qualitative approach and 1% adopted a mixed approach).

According to the literature assessed, the research on the impacts of sugarcane production on ecosystem services goes back to 1961, however, the frequency increased gradually and in the last decade, it became 20 times more abundant (Figure 3).

Most of the literature assessed focused on physical, chemical and microbiological properties of soils, water quality and quantity and resulting soil erosion problems and air quality and pollution. Some literature analysed human well-being including health and food security and very few dealt with biodiversity and land-use change (Figure 4).

3.1. Soil properties

Sugarcane comes from large plantations that are either conventionally grown or mechanised, which puts very high pressure on soil resources in terms of practices adopted and nutrients load and removal and modifies soil physical, chemical, and biological properties.
3.1.1 Soil chemical properties

Soil acidification is a common problem of soils under sugarcane cropping mainly due to the use of N fertilisers (and other major components (P:K) under their different forms) and to the mineralisation of organic matter. Nutrients in soils have been studied for the major components (N:P:K) and their different forms e.g., total N, mineralised N, microbial biomass N, nitrate, ammonium, total P, Olsen-Extractable P, total K, soluble K+ and fixed K+. Some studies included an assessment of other factors such as exchangeable cations and organic matter.

Soil carbon content is another problem that received much attention in the literature; Carbon content change in soils under long-term sugarcane has been reported in the literature (Naranjo et al., 2006; Alaban, 1990; Cerri and Andreux, 1990; Masilaca et al., 1985) and compared to different natural land uses and agricultural cropping patterns (Brackin et al., 2013; Queiroz Rossi et al., 2013; Holst et al., 2012; Souza et al., 2012; Galdos et al., 2009; Sant’Anna et al., 2009; Campos et al., 2007; Silva et al., 2007; Dominy and Haynes, 2002; Cerri and Andreux, 1990) under different soils (Holst et al., 2012; Pankhurst et al., 2005; Dominy et al., 2002) adopting different agricultural practices (Queiroz Rossi et al., 2013; Souza et al., 2012; Stirling et al., 2010; Galdos et al., 2009; Sant’Anna et al., 2009; Graham and Haynes, 2005a; Graham and Haynes, 2005b; Pankhurst et al., 2005; Pankhurst et al., 2003; Graham et al., 2002; Yadav et al., 1994). Most of the studies assessed different components of carbon in the soil such as the total carbon content, organic carbon content, mineralised carbon content, etc., but few studies e.g. Umrit et al. (2014) considered the long-term impact of sugarcane production on other C related indexes such as labile C, lability and lability index, Carbon Management Index (CMI) and Carbon Pool Index (CPI) under different soils and different vegetative cover.

In general, it is evident from the literature assessed that the conversion of pasture land into sugarcane has positive impacts on soil chemical properties (Oliveira et al., 2016; Borges et al., 2014). However, if compared to native vegetation and forests (Oliveira et al., 2016; Anaya et al., 2015; Queiroz Rossi et al., 2013; Da Silva et al., 2012; Souza et al., 2012; Stirling et al., 2010; Ye and Wright, 2010; Castillo and Wright, 2008; Campos et al., 2007; Haynes et al., 2003; Wood, 1985), results showed an initial perturbation of chemical properties followed by a long-term stability at values lower than native vegetation and forests (Morrison and...
This new status quo has been interpreted by some authors, who compared it to the natural systems, as a negative impact of sugarcane production (Chi et al., 2017; Ortiz et al., 2017; Franco et al., 2015); while other authors, comparing it to other agro-systems, considered it a positive long-term impact (Cherubin et al., 2016a; Cherubin et al., 2016b; Mthimkhulu et al., 2016; Anaya et al., 2015; Tavares et al., 2015).

However, management practices have a big influence on soil chemical properties. For instance, nutrients depletion depends on soil types (Satiro et al., 2017; Haynes et al., 2003; Hartemink, 1998b; Hartemink, 1998c; Ali et al., 1986), and it is slower though if good management practices are applied such as irrigation (Van Antwerpen and Meyer, 1996), organic production (Borges et al., 2014), conventional harvesting, green harvesting, trash inoculation or degree of straw removal (Assunção et al., 2018; Liao et al., 2013; Graham and Haynes, 2006; Graham and Haynes, 2005a; Graham et al., 2002; Yadav et al., 1994) and rotational farming (Souza et al., 2012; Stirling et al., 2010; Chorom et al., 2009).

One study assessed soil contamination with toxic heavy metals and showed that mercury concentration in the Everglades soils in Florida (USA), under burnt sugarcane could reach 0.15 mg per kg of soil (Patrick et al., 1994). However, Mendes et al. (2016) have reported that soil chemical contamination varies with soil type and agricultural practices.

The assessed literature showed that chemical properties of sugarcane plantations are directly affected compared to natural habitats i.e. forests. This certainly varies with soil types, with the age of the plantation, and the agricultural practices. The longer the age of the plantation (continuous cropping without any rotational crop), the bigger the impact on soil depletion and unfertilised sugarcane plantations are highly deficient compared to fertilised plantations; burnt plantations are also more affected than green harvesting. In the latter case, soil nutrients are improved if the trash is reused for mulching after harvesting.
3.1.2 Soil physical properties

Recently, mechanisation in sugarcane production is replacing the traditional way based on high labour input. Topsoil would get compacted by tractors and harvesters, which would consequently affect soil physical characteristics such as soil porosity and soil aeration reduction, decrease increase soil resistance and reduce the root system and finally affect the yield. This would also modify the infiltration rate of soils and would increase runoff and soil erosion. Similarly, the traditional burning of sugarcane before harvesting would increase topsoil temperature and would reduce soil hydraulic conductivity which would increase the runoff (Robichaud and Hungerford, 2000). Research on soil erosion under sugarcane was carried mainly in Brazil with an average ranging between 6.5 and 31 t ha\(^{-1}\) yr\(^{-1}\) (Pereira and Ortega, 2010; Macedo, 2007; Sparovek and Schnug, 2001), the average erosion in the USA was between 17 and 18 t ha\(^{-1}\) yr\(^{-1}\) (Bengtson et al., 1998). In Australia Prove et al. (1995) monitored 7 different sugarcane sites estimated the average soil erosion at 148 t ha\(^{-1}\) yr\(^{-1}\), while Lu et al. (2003) using spatial modelling method estimated the national average at 16.1 t ha\(^{-1}\) yr\(^{-1}\). These averages are very high compared to erosion under forest estimated by Lu et al. (2003) at 1 t ha\(^{-1}\) yr\(^{-1}\). Further, under the same slope range (8.5%-12%) and the same rainfall (1,300 mm yr\(^{-1}\)) Macedo (2007) noted that erosion is different under different sugarcane harvesting practices.

Soil physical characteristics vary differently with the soil structure (Satiro et al., 2017; Ahmad, 1996). However, results of the review confirmed the effect of sugarcane production on soil bulk density showed to be higher especially on the top-soils (Umrit et al., 2014; Queiroz Rossi et al., 2013; Holst et al., 2012; Castillo and Wright, 2008; Wright, 2009; Srivastava, 2003; Dominy and Haynes, 2002; Hartemink, 1998c; McGarry et al., 1996; Van Antwerpen and Meyer, 1996; Yadav et al., 1994; Ali et al., 1986; Wood, 1985; Maclean, 1975; Trouse and Humbert, 1961); very few literature studies other factors such as the impact of sugarcane production on saturated hydraulic conductivity (\(K_s\)) which increases on the top-soil under sugarcane reducing drainage (De Los et al., 2014), and infiltration (Bangita and Rajashekhar Rao, 2012) and increasing cone penetration resistance (Usaborisut and Sukcharenvipharat, 2011).
However, as the literature showed, the effect of sugarcane production on these factors varied according to soil structure (Umrit et al., 2014; Usaborisut and Sukcharenvipharat, 2011; Hartemink, 1998c; Ali et al., 1986) and depending on the practices adopted e.g. rainfed and irrigated sugarcane (Van Antwerpen and Meyer, 1996), conventional tillage, zero tillage, ripping and hilling tillage (Bangita and Rajashekhar Rao, 2012; Srivastava, 2003), conventional or mechanised sugarcane and level of mechanisation (Umrit et al., 2014; Queiroz Rossi et al., 2013; Trouse and Humbert, 1961).

3.1.3 Soil biological properties

Soil biological properties are directly affected by the change in chemical and physical properties (Hartemink, 2008). Indeed, changes in soil acidity and soil organic matter as well as changes in bulk density, porosity and aeration would modify biological components in the soil and disrupt microbial activities.

Enzymes activities have been suggested as sensitive indicators of soil biological properties (Dick, 1997; Nannipieri, 1994). The literature assessed showed that natural habitats have the highest enzymes’ activity followed by pasture, while sugarcane presented a low enzymes’ activity (Cardoso et al., 2016; Brackin et al., 2013; Ye and Wright, 2010; Sant’Anna et al., 2009; Zou and Bashkin, 1998; Magarey et al., 1997).

However this activity varies with the field management: unfertilised/fertilised, burnt/green harvesting, trash removal/trash mulching and tillage level (e.g. Castioni et al., 2018; Liao et al., 2013; Stirling et al., 2010; Yadav et al., 2009; Graham and Haynes, 2005a; Pankhurst et al., 2003; Srivastava, 2003; Graham et al., 2002). Summed up, all these factors affect the microbial life in soils (i.e. Bacterial and fungal colonies, pachymetra, actinomycetes, and nematodes), which showed to decline under long-term sugarcane (Holt and Mayer, 1998) and different management practices. Just a few published works suggested a relation between soil pH and abundance of microbial colonies.

3.2 Water resources

The impacts of sugarcane production on water ecosystems could be quantitative where the crop is irrigated and qualitative as a result of leaching of nutrients and chemicals into the
drainage water and their accumulation into the ground or the surface waters (rivers, wetlands, sea).

3.2.1 Quantitative impact

In quantitative terms, most of the literature assessed has been published from case studies in Australia, Brazil, South Africa, the impacts of sugarcane production on water resources vary with the variation of the local agro-meteorological conditions.

Irrigation in Brazilian sugarcane is not yet a limiting factor as most of the production is mainly a rainfed one, relying on natural rainfall to replace water losses by crop evapotranspiration (ET\(_c\)), which ranged according to Ghiberto et al. (2011) between 847 mm and 970 mm a year in the Southeast and according to Macedo (2007) between 1,500 mm and 2,500 mm a year at a national level. However, in the last decade, supplementary irrigation is being applied in the driest areas of the Northeast (Macedo, 2007). While quantitative impacts are still mild in tropical countries, they can be serious in drier climates.

Indeed in Iran water footprint of sugarcane under free drainage could reach 250 m\(^3\) for each tonne produced (Jahani et al., 2017). Further, in Southern Africa where irrigation water is showing an alarming decline, Mhlanga et al. (2006) estimated the average irrigation requirement for sugarcane in Swaziland at 1,000 mm a year. In South Africa, irrigation requirements ranged between 731 and 1,062 mm a year (Olivier and Singels, 2012; Van der Laan et al., 2012). Comparing the ET\(_c\) of the previous research with the estimates of ET\(_c\) estimated by Schmidt (1997) for South Africa, we find it much lower. Another study carried out in South Africa on two different soil types simulated irrigation water requirements of sugarcane using climate data for the period 1968-2003 and showed that IWR could vary between 835 mm and 1,496 mm depending on the irrigation schedule adopted (Singels and Smith, 2006).

In the USA, Shih and Gascho (1980) estimated these irrigation requirements between 1,055 mm and 1,360 mm per year, and in Australia, they were estimated between 855 mm and 1,642 mm a year (Thorburn et al., 2011).
Kshirsagar (2006) showed that irrigation water requirements in India are about 1100 mm under conventional sugarcane farming systems that can be reduced to 500 mm adopting organic farming (45% reduction).

Finally, literature has confirmed the significance of irrigation management to reduce irrigation quantities and water footprint of sugarcane production (Jorrat et al., 2018; Carvalho et al., 2016; Olivier and Singels, 2015; Sandhu et al., 1980).

### 3.2.2 Qualitative impact

Agricultural practices on a sugarcane farm such as fertilisation and spraying for their importance could increase leaching and water contamination with nutrients and agrochemicals leading to ecotoxicity, eutrophication, and acidification (Prasara-A and Gheewala, 2016).

Assessed literature showed that the impact of sugarcane production on water quality can be expressed with a deterioration of its chemical properties and contamination with nutrients and agrochemicals and can be assessed at field level analysing drainage water and runoff (e.g. Nachimuthu et al., 2016; Oliver et al., 2014; Agostinho and Ortega, 2013; Davis et al., 2013; Masters et al., 2013; Agostinho and Ortega, 2012; Webster et al., 2012; Thorburn et al., 2011; Udeigwe et al., 2010; Ghiberto et al., 2009; Faithful et al., 2007; Mhlanga et al., 2006; Stewart et al., 2006; Faithful and Finlayson, 2005; Roth et al., 2003; Ng Kee Kwong et al., 2002; Rice et al., 2002; Bengtson et al., 1998; Southwick et al., 1992), at groundwater level (e.g. Alves et al., 2014; Rasiah et al., 2013; Camenzuli et al., 2012; Shaw et al., 2012; Thayalakumaran et al., 2008; Yu et al., 2008; Cerdeira et al., 2007; Rasiah et al., 2005), and at the river of the coastal level (e.g. Allan et al., 2017; Rohde et al., 2006; Mitchell et al., 2005; Muller et al., 1999).

Different research investigated different indicators (chemical quality, nutrients contamination, herbicides contamination) to prove different conclusions, which varied between slight to severe contamination of water bodies, and even urban water networks (Li et al., 2018), due to the excessive use of production inputs.
Studies comparing banana farms and sugarcane farms in Australia showed that under banana field pH of drainage is higher and electrical conductivity (EC) is lower, which makes drainage more acidic under banana but more saline under sugarcane (Faithful et al., 2007) this could be due to the high N and P concentrations found under banana compared to sugarcane fields, but this partially contradicted what the same authors in a previous study have found (Faithful and Finlayson, 2005), i.e. higher N concentrations under sugarcane which agrees with Rohde et al. (2006) and Bramley and Roth (2002) finding that N and P concentrations under sugarcane in Australia are higher than under grazing or forestry.

Other studies compared water contamination with nutrients under different management practices and showed that this contamination is related to the fertilisation rates (Thorburn et al., 2017; Webster et al., 2012; Yu et al., 2008; Bengtson et al., 1998), the application timing of fertilisers e.g. fertilisers applied before rains would increase losses (Ng Kee Kwong et al., 2002), and the overall farm management e.g. agro-ecological sugarcane farms have less nutrients pollution than conventional farms (Agostinho and Ortega, 2013; Agostinho and Ortega, 2012). Further, the concentration of suspended and dissolved solids is higher under manual harvesting with pre-burning (Udeigwe et al., 2010).

Mhlanga et al. (2006) assessed water quality from sugarcane fields in different seasons in Swaziland and showed seasonal deterioration of water quality in summer and autumn seasons compared to winter and spring.

Other literature assessed water contamination with agrochemicals mainly in Australia (e.g. Nachimuthu et al., 2016; Davis et al., 2013; Camenzuli et al., 2012; Shaw et al., 2012; Rohde et al., 2006; Mitchell et al., 2005; Muller et al., 2000), in Brazil (e.g. Agostinho and Ortega, 2013; Agostinho and Ortega, 2012; Cerdeira et al., 2007; Lanchote et al., 2000) and the USA (Yu et al., 2008; Bengtson et al., 1998; Southwick et al., 1992). The results showed that waters in sugarcane areas contained pesticides and herbicides concentrations, mainly “Ametrin” “Diuron”, “Triazine” and “Hexazinone” all of which are molecules highly used in sugarcane growing. Further, two studies showed that crop management in terms of row spacing and spraying practice could significantly reduce contamination of water (Oliver et al., 2014; Masters et al., 2013).
Finally, this variability in results of the literature assessed proves that farm management is the key to reduce nutrients losses on the farm under any selected crop and improve water quality its toxicity by agro-chemicals.

3.3. Air quality

In the recent literature, atmospheric pollutants have received particular attention in sugarcane agro-systems especially for the pre-harvest burning practiced to facilitate the harvesting and from the fertilisation of the crops. It has been proved that CO$_2$ emissions from sugarcane farms (Bicalho et al., 2014; Baillie and Chen, 2012) are higher than other farms in Australia (soybean, watermelon) unless soil preparation is well managed. Panosso et al. (2011) and Panosso et al. (2009) estimated CO$_2$ emissions from burnt sugarcane in Brazil, to be 25-30% higher than green harvesting. However, in terms of ozone depletion, Chandra et al. (2018) have shown that sugarcane production has the least impact.

The pre-harvest burning has a direct impact on the environment with the emission increase of different atmospheric pollutants (Mugica-Álvarez et al., 2018; Agostinho and Ortega, 2013; Agostinho and Ortega, 2012). Other impacts are also on human well-being as many pollutants could have mutagenic and carcinogenic properties (Cristale et al., 2012; Silva et al., 2010; Umbuzeiro et al., 2008; Zamperlini, 1997).

According to the literature, N$_2$O emissions [in CO$_2$ equivalent] could vary between different soil types (Wang et al. 2016a) being six times lower in light soils. They also could double with nitrogen fertilisation compared to unfertilised production (Wang et al., 2016a), and the source of Nitrogen [urea, ammonium, straw, etc.] could determine the amount of N$_2$O emissions (Dattamudi et al., 2016; Wang et al., 2016b).

Agricultural practices are fundamental for a win-win production strategy in managing the total emissions (Bordonal et al., 2018; Chalco Vera et al., 2017; Fracetto et al., 2017; Pongpat et al., 2017). Indeed green harvesting with a rate of straw removal of about 50% (Gonzaga et al., 2018; Vasconcelos et al., 2018; Pitombo et al., 2017) combined with the optimal fertilisation rates and types (Dattamudi et al. 2016; Siqueira Neto et al. 2016), irrigation management (Fonseca da Silva et al., 2017; Cardozo et al., 2016) and optimisation of the
machine traffic in the field (Pryor et al., 2017; Panosso et al., 2012); are all necessary practices to reduce emissions and improve production.

Indeed, fertilisation management increases N sequestration (Signor et al., 2013; Allen et al., 2010; Denmead et al., 2010; Macedo et al., 2008; Weier, 1999; Weier, 1996), and field management increases C sequestration such as straw mulching vs no mulch (Corradi et al., 2013), no-till or reduced till versus conventional tilling and mechanical harvest versus manual (La Scala et al., 2006). Brito et al. (2009) assessed the impact of field topography in reducing soil CO₂ emissions and showed that the concave part of a furrow has fewer emissions than the foot slope.

Contrarily to what has been published, Eustice et al. (2011) showed that mechanical harvesting in South Africa would reduce NH₃ emissions (25 kg CO₂ eq ha⁻¹ less NH₃ in mechanical harvesting per season) and would save a lot of CH₄ emissions from burning (60 kg CO₂ eq ha⁻¹ CH₄ saved), but it would not reduce the total crop emissions as they estimated the total CO₂ eq emissions for burnt sugarcane at 2,252 kg CO₂ eq ha⁻¹ compared 3,443 kg CO₂ eq ha⁻¹ for mechanical harvesting.

### 3.4. Human well-being

For sustainable sugarcane production, the sector should increase the socio-economic aspects of operating farmers in terms of employment and employability conditions, income, food security, and health which all participate in their general well-being. However, the literature assessed showed contradiction in the outcomes except for the impacts of sugarcane production on human health.

#### 3.4.1 Impacts on health

Agricultural practices in sugarcane farming are the major cause of health problems. This mainly happens where the conventional pre-harvest burning is still the prevailing practice with consequences on the respiratory system and lung function (Kasambala Donga et al. 2018; Le Blond et al., 2018; Arbex et al., 2014; Goto et al., 2011; Ferreira-Ceccato et al., 2011; Romeo et al., 2009; Uriarte et al., 2009; Arbex et al., 2000; Arbex et al., 2007; Cançado et al., 2006). The development of cancerogenic symptoms due to mutagenicity risks is also discussed in
different studies which relate it to sugarcane burning (Du et al., 2018; Alves et al., 2016; Cristale et al., 2012; Prado et al., 2012; Sisenando et al., 2012; Devendra, 1999; Brooks et al., 1992; Rothschild and Mulvey, 1982). Urinary functions and chronic kidney-related symptoms have been raised in the literature (Wesseling et al., 2015; Crowe et al., 2013; Peraza et al., 2012; Prado et al., 2012). Other minor health-related problems have also been noticed such as symptoms of stress, allergic reactions and different injuries (Prado et al., 2012; Arbex et al., 2010; Robins et al., 1998).

Furthermore, a few studies have discussed the inter-linkage between impacts of sugarcane production on biodiversity and the increased risk of health-related problems i.e. skin irritation, headache, coughing, running nose (Kasambala Donga et al., 2018), malaria vectors’ resistance and the use of pesticides in sugarcane production (Dusfour et al., 2010). The socio-economic impacts of sugarcane production and their relation to health impacts have also been discussed by Richardson (2010) who found that sugarcane labour migration in Zambia contributes to HIV/AIDS infection at 16% to 22%.

3.4.2 Impacts on farmers’ income

Income generation from sugarcane production is very site-specific. Different studies in Kenya generated different outputs. In the late eighties, Kennedy (1988) and Kennedy and Cogill (1988) showed that income from sugarcane farming is much higher than other types of farming with a higher income from commercialisation of agricultural products (25% higher income and 60% higher commercial income). However, a year after the same other revealed that maize farming in Kenya is more beneficial than sugarcane farming and the income from the latter is about 17% lower arguing though that the income per day per family labour is higher for sugarcane as maize production employs more work-days for family and hired labour (Kennedy, 1989).

Studies from Ethiopia, Belize and Thailand showed that salaries of sugarcane growers are lower compared to other growers, but this is correlated to the size of the farm and the practices adopted (Chi et al., 2017; Prasara-A and Gheewala, 2016; Wendimu et al., 2016).
Experiences from Malawi, Mozambique, Swaziland, Brazil reflect a different situation, where sugarcane areas seem to be better off compared to non-sugarcane area, with high living standards in terms of poverty, life expectancy, access to school, electricity and sewer system and other services (Mudombi et al., 2018; Machado et al., 2015a; Moraes et al., 2015; Macedo, 2007).

It has been noted, however, that this well-being is contributing to an increase in land price (Palludeto et al., 2018), especially in Brazil, where researchers have studied the impacts of sugarcane expansion on small farmers who are not protected by the public policies and end up losing control of their lands, and are transformed to cheap labour for the mills (Petrini et al., 2017; Frate et al., 2015).

Besides, different studies showed that farm management in terms of agricultural practices is an important factor to generate more income (Jha et al., 2015). Kshirsagar (2006) showed that organic sugarcane farming in India has 10.8% higher profits compared to conventional ones, and Liao et al. (2013) in China showed that trash addition could generate additional 10.9% profits to farmers.

3.4.3 Labour conditions

The literature assessed showed that labour requirement in sugarcane farming is lower than maize farming in Kenya (Kennedy, 1989); and in China, the average labour requirement for sugarcane farming, was calculated to be 54 person-days against 72 person-days for cassava farming (Zhang et al., 2011). However, Kshirsagar (2006) noted that organic sugarcane farming improves the sustainability of the sector increasing human labour by 21.5%.

Labour conditions have been raised by many studies because it could lead to several socio-economic and health problems which could affect human well-being considerably and many cases have been noted in the literature (Wendimu et al., 2016). For instance, in a survey led in South Africa Robins et al. (1998) reported that adding to health problems workers are facing in sugarcane fields, 14% reported receiving moral or physical aggression by farm owners; 9% reported being threatened with a knife or gun by these same individuals. Also, Xavier et al. (2011) mentioned the deterioration of cutters conditions In Brazil (workers exploitation, cases
of death) due to the adoption of payment based on the amount of product and not per hour, with a continuous increase in the production quota. Recently the number of cane cutters is falling after the introduction of mechanical harvesters. The number of workers rescued in situations comparable to slavery is between 10% and 51% depending on the year.

Even though advances in the direction of “social responsibility” have intensified in Brazil towards more ethical actions in the sugarcane production (Macedo, 2007), many problems related to labour migration and health problems have been reported from other sugarcane producing countries: In Zambia, for instance, labour migration participates in HIV infection as mentioned by Richardson (2010), who stated also cases of households displacement in Mozambique (1,100 households displaced) due to water and land grabbing for the expansion of sugarcane companies. Many cases of labour exploitation in Mozambique have been perceived ($50 US per month), including threats to death to stop labour activism and work-related death. Further, health risks related to environmental pollution have been assessed in the literature in Kenya (Kennedy, 1989) and in Brazil (Cristale et al., 2012; Umbuzeiro et al., 2008; Cançado et al., 2006).

3.4.4 Food Security

Little scientific evidence has been published regarding the impact of sugarcane production on food security, the literature assessed did not depict any relation between sugarcane and food insecurity. Kennedy (1988) and Kennedy and Cogill (1988) showed that agricultural production used for own consumption is higher in non-sugarcane farms in Kenya, and later on, Kennedy (1989) has found a negative correlation between sugarcane production and increased malnutrition.

Comparing organic to conventional sugarcane production Kshirsagar (2006) showed that organic sugarcane farming not only increases income but improves also yield stability, therefore, food security (Coefficient of variation for organic sugarcane is 26.3% while the coefficient of variation for conventional sugarcane is 57.7%).

Furthermore, recent studies in Brazil have shown that sugarcane improves food security and sugarcane growers, given the higher socio-economic standards, have higher food crop
production, because they reveal higher spending compared to the control in terms of food crop inputs (Defante et al., 2018; Herrmann et al., 2018).

3.5. Biodiversity

The importance of soil biodiversity resides in the fact that it is used as a soil quality indicator (Doube and Schmidt, 1997), as the micro-fauna species are involved in soil processes. To date, very little attention has been paid to the impact of biofuel crops on biodiversity which could depend on the feedstock produced and the type of land converted (Campbell and Doswald, 2009). Biofuel production is in general considered a threat to biodiversity of ecosystems (Groom et al., 2008), in particular, induced habitat destruction (Lee, 1985) and other drivers such as invasive species and disease (Fraser, 1995; Edwards et al., 1994), loss of soil fauna (Franco et al., 2016), pollution from intensive inputs use (Felício et al. 2018; Schiesari and Corrêa, 2015; Tadini et al., 2015), aquatic resources diversity and quality (Nhiwatiwa et al., 2017; Zeni et al., 2017).

The number of literature reviewed which deals with the impact of sugarcane production on biodiversity (18 references), confirms what has been mentioned about the absence of attention for this kind of research. Literature that has been assessed focused mainly on species richness in soils and waters such as fish, earthworms, termites, ants, preys, spiders and amphibians (Santos et al., 2018; Zeni et al., 2017; Stefani Margarido et al., 2013; Dlamini and Haynes, 2004; Miranda et al., 2004; Haynes et al., 2003; Zou and Bashkin, 1998; Ali et al., 1986) and results showed a reduction in these communities between sugarcane and other land uses. They also noted a difference in the number of these communities between different management practices within sugarcane fields.

Two studies have analysed mammals’ abundance (Hurst et al., 2014; Gheler-Costa et al., 2013), comparing different sugarcane management practices and they concluded that mammals’ abundance is correlated to the intensity of production.

However, the sugarcane expansion and intensification are not only limited to species abundance, as Degefa and Saito (2017) have found a relation between sugarcane expansion, species abundance, and species’ resources requirements. Other aspects of biodiversity loss
have been evaluated in terms of eco-toxicity generated by high inputs use in sugarcane production (Felício et al., 2018; Qian et al., 2017; Haynes et al., 2000), and the correlated risks on species extinction, or the invasion of a new insect acquiring more resistance to pesticide (Dusfour et al., 2010).

3.6. Land-use change

The increased demand on bioethanol has boosted the demand for sugarcane plantations, leading to direct and/or indirect land-use change which is becoming a major concern for two main reasons:

- Sugarcane plantations would expand on natural forests and agricultural land reducing crop production and threatening food security and endangering biodiversity and the quality of the environment.
- Sugarcane expansion would have an important threat to biodiversity with the conversion of natural vegetation into sugarcane plantations. This concern was subject to few studies mainly in Brazil the host of the largest part of the Amazon rainforest (around 60%), registering high levels of deforestation.

Indeed, Zhang et al. (2011) showed a negative and significant correlation between rice and sugarcane plantations in China. This is not the case in Brazil, sugarcane expansion this is not affecting food crop production, even if expansion is moving and at fast rates (Adami et al., 2012; Nassar et al., 2008). It has been estimated in 2007/08 at about two million hectares (Zuurbier and Van de Vooren, 2008), and it has been calculated between 30 and 55% (Scarpare et al., 2016; Machado et al., 2015b). In Brazil, the expansion of sugarcane replaced mainly other cropping lands on degraded pasture (Bordonal et al., 2018; Taniwaki et al., 2017; Andrade de Sá et al., 2013). Literature has suggested that land-use change in a forest or a reforestation area in Brazil was only 0.6% for sugarcane expansion (Adami et al., 2012; Adami et al., 2011; Nassar et al., 2008).

A beneficial effect of degraded land conversion to sugarcane has been monitored by many others who noted an improvement of organic carbon and nutrients accumulation in
transformed soils (Romeu-Dalmau et al., 2018; Sattolo et al., 2017; Cherubin et al., 2015). Yet a negative impact on water resource quality has been observed by (Taniwaki et al., 2017).

Some authors argued that sugarcane expansion has an indirect impact on biomes even when the replacement is indirect. Unlike direct land-use change, indirect land-use change is more complicated to evaluate as its definition and methods are still under development (Nassar et al. 2008). However, in Brazil, a negative and statistically significant correlation has been confirmed between deforestation and the expansion of sugarcane fields (Andrade de Sá et al., 2013).

4. Conclusions

In this research, we implemented the systematic review methodology to assess the impacts of sugarcane production on the ecosystem services adopting the millennium ecosystem assessment (MA) which accounts for the trade-offs existing in the inter-linkage of these ecosystems.

It was noted that the studies assessing the impacts of sugarcane production focused on Brazil, Australia, USA and South Africa (= 75% of the literature), while many other countries such India, China, Thailand, Pakistan were not sufficiently included in the literature, even though they are international leaders in terms of sugarcane production.

In summary, the literature assessed – in all countries comprised in the SR – showed a direct impact of long-term sugarcane production on i) soil properties i.e. reduction of soil fertility, deterioration of soil physical properties and consequently the deterioration of the biological properties of soils; ii) water resources particularly pollution of ground and surface water bodies; iii) air quality, in particular with conventional sugarcane production based on pre-harvest burning; iv) human well-being including farmers’ income, employment, and labour conditions, health conditions v) biodiversity; vi) land-use change with the direct impacts as well as the indirect impacts.

All the assessed literature lead us to the conclusion that sugarcane, like all agro-systems, could have different externalities, some are positive and others are negative. Thus, the summarised impacts have shown to be directly related to management rather than to the
crop. This means decision making is crucial to make any agro-system sustainable or unsustainable. Indeed, the literature assessed evidence where these impacts could be reduced and sugarcane production could improve soil properties, water, and air quality, biodiversity and human well-being in case good management practices are adopted, organic sugarcane farming and agro-ecological sugarcane farming could also reduce these impacts.

Whilst the evidence collected suggests impacts of sugarcane production on different ecosystem services, the literature studied failed to include the inter-linkage in the impacts of sugarcane production and therefore to evaluate the ecosystems services and human well-being with respect to the Millennium Ecosystem Assessment (MA) framework to account for the trade-offs between ecosystem services and human well-being.

According to Kropff et al. (2001), this could be related to the absence of interconnected analysis involving multidisciplinary approaches given the complexity of the agro-ecosystem from one hand; and from another hand the conceptual and methodological barriers to using sustainability as a criterion for guiding change in agro-ecosystems (Hansen, 1996). However, many other scholars have tried in the past to integrate different production aspects into frameworks and modelling tools to improve agricultural and sugar systems’ sustainability.

Finally, based on these findings and the limitations encountered and for a sustainable development of the sugarcane sector, this review suggests further research based on the MA framework, which has been suggested by El Chami et al. (Forthcoming), to cover all ecosystem services and particularly in geographic locations where studies are missing to allow an integrated and consistent evaluation of sugarcane production.

5. References


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Table 1. Main producers, world production and harvested area of sugarcane in 2012

<table>
<thead>
<tr>
<th>Origin</th>
<th>Production</th>
<th>Area Harvested</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tonnes</td>
<td>Hectares</td>
</tr>
<tr>
<td>Brazil</td>
<td>758,548,292</td>
<td>10,184,340</td>
</tr>
<tr>
<td>India</td>
<td>306,069,000</td>
<td>4,389,000</td>
</tr>
<tr>
<td>China</td>
<td>209,586,066</td>
<td>2,754,210</td>
</tr>
<tr>
<td>Thailand</td>
<td>102,946,001</td>
<td>1,368,269</td>
</tr>
<tr>
<td>Pakistan</td>
<td>73,401,199</td>
<td>1,216,894</td>
</tr>
<tr>
<td>Mexico</td>
<td>56,954,993</td>
<td>77,003</td>
</tr>
<tr>
<td>Australia</td>
<td>36,561,497</td>
<td>453,470</td>
</tr>
<tr>
<td>Colombia</td>
<td>34,638,019</td>
<td>397,387</td>
</tr>
<tr>
<td>Guatemala</td>
<td>33,758,389</td>
<td>278,967</td>
</tr>
<tr>
<td>USA</td>
<td>30,153,010</td>
<td>365,880</td>
</tr>
<tr>
<td>Rest of the World</td>
<td>303,704,955</td>
<td>5,173,620</td>
</tr>
<tr>
<td>Total</td>
<td>1,946,321,421</td>
<td>27,354,040</td>
</tr>
</tbody>
</table>

(Source: FAO 2019)
What are the impacts of sugarcane production on ecosystem services and human well-being?

Google, Google Scholar, Organizations' websites
ScienceDirect (1,433)
Web of Science (512)
SCOPUS (644)
DOAJ (126)

Remove Duplicates

2,200 records

1st Screening

649 references

2nd Screening

336 references

Figure 1: Schematic overview of the SR process
Figure 2: Distribution of the literature reviewed (%) by country

Table 2. Percentage of the literature reviewed by the main countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazil</td>
<td>39.9</td>
</tr>
<tr>
<td>Australia</td>
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</tr>
<tr>
<td>USA</td>
<td>7.9</td>
</tr>
<tr>
<td>South Africa</td>
<td>7.3</td>
</tr>
<tr>
<td>India</td>
<td>3.3</td>
</tr>
<tr>
<td>Others</td>
<td>24.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>
Figure 3: Distribution of the literature over the years

Figure 4: Distribution of the literature (%) by the impact on the ecosystem services