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Definition of the optimal cultural practices according to the economic and environmental sustainability of sweet sorghum

Composition of the consortium

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Definition of the optimal cultural practices according to the economic and environmental sustainability of sweet sorghum

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1. Introduction

The definition of optimal crop production practices is a challenging task especially in relation to current global issues such as increased CO_2 gas emissions, food security and fuel prices, increased poverty and growing populations. From an agronomic perspective the optimization of agricultural practices should lead to maximize yields, this can be done by the use of chemical fertilizers, agro-chemicals, agricultural machineries, irrigation, plant breeding, etc. However, maximizing productivity with little or no consideration for long-term environmental sustainability may led to negative consequences (e.g. water pollution due to excessive use of agrochemicals, exhausted and degraded soils, increased emissions due to inefficient energy consumption by machineries and chemical production, etc.). In turn, these environmental consequences have negative repercussions on the ability of the agro-ecosystems to produce the desired products quantitatively and qualitatively with still economic benefits. So, from a sustainability perspective the optimization of sweet sorghum production should seek to minimize its environmental impacts with the maximum productivity possible to ensure a favorable economic return to the farmer. In fact, the optimization of the agricultural practices would result not only in reduced cost (less material and labor costs), but also in reduced impacts on the environment, lower CO_2 emissions, and with the appropriate quality and quantity of the feedstock required (Fig. 1).

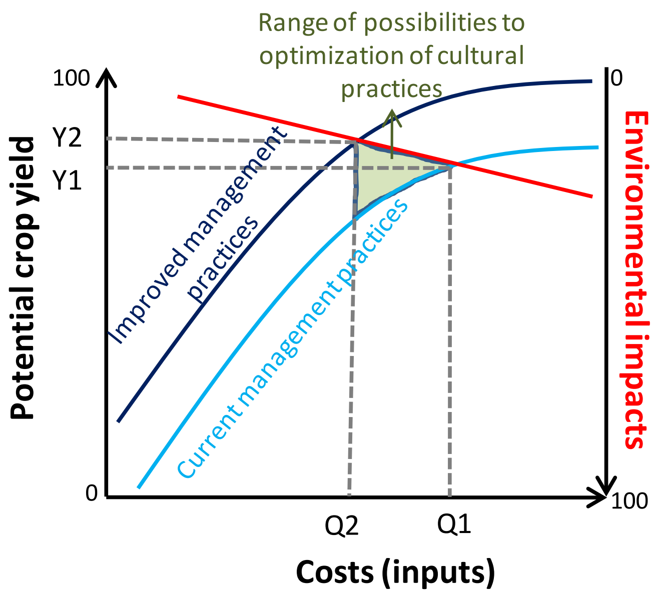

Fig. 1. Definition of the optimal cultural practices according to the economic and environmental sustainability of sweet sorghum scheme. The range of possibilities to optimize cultural practices is defined by the tradeoff between the use of improved crop management practices which increase yields (Y2) and reduce cost (Q2) and at the same time minimize environmental impacts.

From the integrated sustainability assessment performed in WP6 within the Sweetfuel project taking into account several scenarios (for more details on such scenarios see IFEU, 2014 report; Reinhardt et al., 2014) in mature and large-scale sweet sorghum production systems emerged that several environmental, economic, and social advantages of cultivating sweet and biomass sorghum for bioenergy production are possible (Reinhardt et al., 2014). But, at the same time, it was evidenced that nitrogen fertilization and field emissions derived from fertilization are the most important impact categories affecting all sweet and biomass sorghum production for the considered scenarios (Fig. 2).

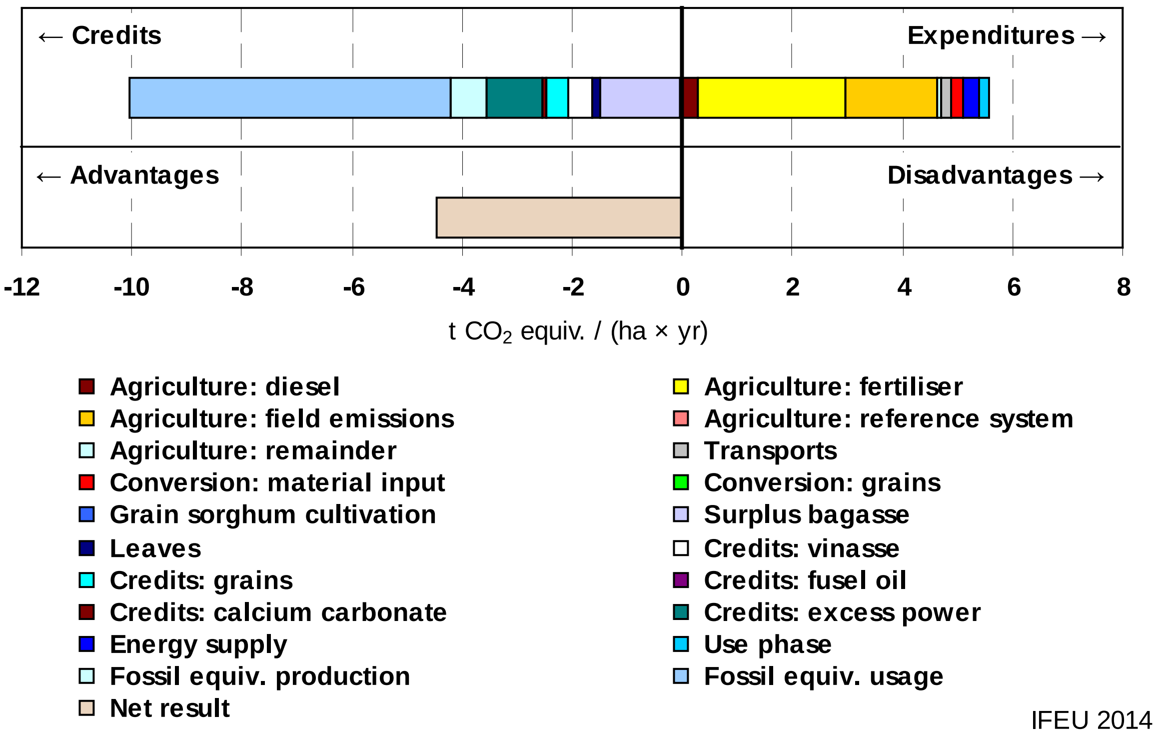

Fig. 2. Contributions of individual life cycle steps (coloured sections) to the overall net result (light brown bar) of sweet sorghum ethanol production in the cane fallow scenario for the environmental impact category greenhouse effect. Results are based on typical cultivation and conversion conditions (source: IFEU 2014; Reinhardt et al., 2014)

Deciding the optimal dose of fertilizer is complicated because many factors can influence it. Besides that, due to the customary current N management strategies, N losses predominantly due to denitrification, gaseous plant emissions, surface runoff, volatilization, and leaching specially on coarse textured soils are common. Such losses raise concerns about water contamination and greenhouse gas emissions. In addition to that, low nitrogen use efficiency (NUE) reduce the economic returns from fertilizer inputs (Blaylock et al., 2005). Raun and Johnson (1999) estimated that in average only around 33% of the N fertilizers applied is recovered/used by the plant. Therefore, the 67% of N lost accounts for a large window of opportunities for improving the economic returns and reducing the environmental impacts associated with current management practices. From the agronomic point of view, improved nitrogen use efficiency by reducing N losses or increasing the recovery in plant biomass could guarantee the sustainability of the production system. Moreover, organic fertilizers which are a valuable source of N (e.g. composted by-products of plant residues from the increasing cellulosic ethanol industry) can further contribute to the reduction of environmental impacts of current fertilization practices (Barbanti et al., 2011). The definition of appropriate best management fertilization practices such as the use of right fertilizer, the right amount, right timing and placing of nitrogen could maximize the nitrogen uptake by the plants. However, the meaning of the right management practices on environmental terms can be quite different from the agronomic or economic point of view. Therefore, in general lines it could be said that the key to optimize the tradeoff between yield, economical benefits, and environmental protection for optimized sweet sorghum management practices could be achieved by better synchronization between the timing of application and crop demands, taking into account the required amount of the right fertilizers, its uniform spatial/temporal distribution at the right place in the soil, the demand changes related to the crop ontogeny, and price of N fertilizers. Therefore, the development of balanced N management strategies and accessible to all farmers is crucial to develop a sustainable sweet sorghum production systems under different production scenarios.

2. Optimization of fertilizer management practices

A way to reduce nutrient losses while improving productivity and maintaining soil fertility, as indicated before, is the use of fertilizer best management practices (FBMP) which consist simply (but not always easily to achieve in practice) in applying the correct nutrient in the amount needed, at the right time and place to meet crop demands. Together with the best nutrient management practices, appropriate agronomic practices (i.e. selection of variety, planting date, hybrid maturity, row-spacing, seeding rates, plant population, integrated pest management, weed control, disease control, etc.) would lead towards optimizing sweet sorghum production potential.

Among the FBMP's, the **right time** of application make nutrients available when the crop needs them the most. The synchrony between crop demand and nutrient supply would improve nutrient use efficiency, especially in the case N fertilizers (Roberts, 2008). In grain sorghum split applications during the growing season, rather than a single pre-planting application, resulted in markedly improvements in N recovery and yield (more than 1 Mg ha^{-1} of extra grain yield compared to a single broadcast application; Tandon and Kanwar, 1984). As for sweet sorghum, the timing of fertilization is also more important than the fertilization rate (Guiying et al., 2000; Almodares and Darany 2006). Almodares and Darany (2006) indicated that plant height, stem diameter, and dry matter yield were increased with nitrogen fertilization being applied at the vegetative stage compared to fertilization being done at the reproductive stage. This could be closely related to the reported rapid sorghum increase in nitrogen uptake between the 4^{th} and 10^{th} leaf stage (Vanderlip, 1979; Fig. 3). Moreover, Freeman et al. (1973) indicated that late N applications have negative effects on the juice quality, therefore they should be avoided in the case that ethanol production would be the sole production scenario.

Since most of the available commercial N fertilizers are highly water soluble or react rapidly to produce plant available forms of N, they are susceptible to large losses if such high availability period do not coincide with the aforementioned period of high nutrient uptake rates. Therefore another approach to synchronize the release of N with the crop uptake needs is the use of N stabilizers or controlled release fertilizers (Blaylock et al., 2005; Gioacchini et al., 2006; Roberts, 2008). These fertilizers, however, are usually most useful for crops that have prolonged periods of modest nitrogen needs. For example they usually give satisfactory results with high-value crops such as horticulture crops or turfgrass (Roberts, 2008). A mini review of the literature showed that there is limited experience on the use of controlled release fertilizer on sorghum and even more limited in the case of sweet and biomass sorghum, which are relatively new crops and therefore their agronomic management are not well developed. However, the few related studies available on grain sorghum suggest that such fertilizers could have the potential to improve the N-use efficiency while maintaining or improving productivity. For example, Ahmed et al. (2007) found that controlled release N fertilizers, compared to urea and ammonium nitrate, produced greater yields in two grain sorghum cultivars in a sandy soil. It remains, however, to determine if the increased costs of the product used could be offset by the additional yields. As for the use of N stabilizers that inhibit nitrification, results are somehow contradictory and highly dependent on climatic and soil conditions of the scenarios considered. Mascagni and Helmsa (1989), did not find any effects of dicyandiamide (DCD) a nitrification inhibitor on sorghum grain yield in either poorly or well drained soils. On the other hand Frye et al. (1989) reported increased yields resulting from DCD use in Alabama soils. Therefore, the consistent benefit from DCD use is still not well defined for sorghum, and this may be even less clear in the case of sweet and biomass sorghum.

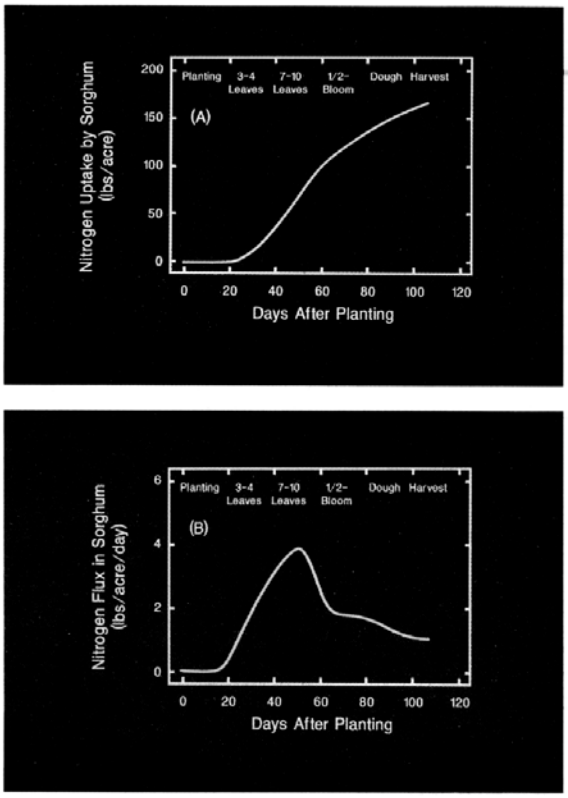

Fig. 3. Cumulative seasonal nitrogen uptake (A) and daily nitrogen fluxes (B) patterns for grain sorghum at a yield level of 7560 lbs. per acre (after Vanderlip, 1979. How a sorghum plant develops. Publication No. 1203. Kansas State University).

As for any other cultivated crop, the right fertilization rate for sweet sorghum depends on the **fertility level of the field** on which is grown, on the previous fertilizer additions, the crop history of the soil, etc. but in general sweet sorghum is less demanding than other row crops. It is reported, for example, that sweet sorghum requires almost 40% less nitrogen fertilizers than maize (Smith and Buxton, 1993). In any case, nitrogen availability exerts the greatest effect on yield, but the reported results for the right amount in sweet/biomass sorghum are somewhat contradictory (Zegada-Lizarazu and Monti, 2012). For example, nitrogen fertilization (ranging from 0 to 134 kg N ha^1) always increased the sugar yield on clay soils, whereas in loam soils a significant sugar response was recorded only if the sweet sorghum was planted after maize, but in most soils a minimum of 67 kg N ha^{-1} was required to optimize yields (Holou and Stevens, 2012). In another study, the added nitrogen fertilizers (0, 60 and 120 Kg N ha^{-1}) to a sweet and a fiber sorghum cultivars had little discernible effects on total productivity (Barbanti *et al.*, 2006). On the other hand Wiedenfeld (1984) demonstrated that 224 Kg ha^{-1} of nitrogen fertilization reduce the juice quality and therefore the fermentable sugars production. Besides, N uptake efficiency was reduced from 33% (at a fertilization rates of 112 Kg ha^{-1}) to only 17% when the fertilization rate was 224 Kg N ha^{-1}. The computed ethanol yields increased from no nitrogen fertilization to 112 kg N ha^{-1}, indicating that the reduction in juice quality was compensated by the increased biomass, but the similar yield achieved by the added nitrogen fertilizer (112 and 224 kg N ha^{-1}) suggest that moderate to low fertilization rates would be enough for producing good ethanol yields and reduce the costs and environmental risks of high fertilization levels. In any case, in most of the considered scenarios, intensive monoculture agriculture relies heavily on external inputs. Therefore the large dependence on agrochemicals constitutes a great challenge to the long-term productivity and sustainability of continuous sorghum monoculture, due to enhanced soil physical degradation risks, environmental problems, and increased use of non-renewable energy sources (Bullock 1992; Karlen et al., 1994; Giller et al., 1997; Tilman et al., 2002; Malezieux et al., 2009). On the other hand, crop rotations can reduce the use of external inputs through internal nutrient recycling, maintenance of the long-term productivity of the land, avoidance of accumulation of pests associated with monoculture, and consequently increase crop yields (Bullock, 1992; Gebremedhin and Schwab, 1998; Peel, 1998; Krupinsky *et al.*, 2002). Therefore the nitrogen application levels, its cost and environmental impacts could be reduced if sorghum is grown in well defined crop rotations. The yields of sorghum, for example, were increased when grown in rotation with different crops under different environmental conditions (Table 1; Zegada-Lizarazu and Monti, 2011). This could be due to the capacity of the legume crops to provide some of the nitrogen required by sorghum. Legume-sorghum rotation studies indicated that the legumes could contribute between 80 to 135 kg N ha^{-1} to sorghum (Blevins et al., 1990; Varvel and Wilhelm, 2003; Wortmann et al., 2007; Holou and Stevens, 2012) which is an amount close to the minimum required amount reported in other studies (Holou and Stevens, 2012). Moreover, Kaye et al. (2007) indicated that the fixed N by a preceding soybean crop accounted for 35% to 41% of the improved yields of sorghum. Therefore the increased availability of N was not the only reason for the increased yields of sorghum in rotation with soybean. In fact, Bagayoko (2000) showed evidence that higher infections by arbuscular mycorrhizae of sorghum roots grown in rotation with legumes also contribute significantly to increased yields, compared to sorghum monoculture.

Table 1. Effect of crop rotations on mean grain and stover yields of sorghum (Mg ha^{-1}) under different environmental conditions. Values in parenthesis represent the sorghum stover production (from Zegada-Lizarazu and Monti, 2011)

Previous crop	Sorghum yield in Australian rotations[a]	Sorghum yield in USA rotations	Sorghum yield in Sub-Saharan rotations[d]
Cowpea	7.64	–	0.94 (1.38)
Sunflower	7.63	–	1.03 (1.63)
Mungbean	7.43	–	–
Pigeon pea	7.22	–	–
Soybean	7.15	5.00 (10.9)[b]	1.00 (1.56)
Wheat	–	5.22 (9.5)[c]	–
Oat + clover	–	5.30 (12.6)[b]	–
Sorghum	6.84	3.40 (7.4)[b]	0.57 (0.89)

a Taken from ref. [47]. Average data of two years.
b Taken from ref. [48]. Average data of four years.
c Taken from ref. [88]. Average data of three years.
d Taken from ref. [78]. Average data of two years.

For an efficient use of fertilizers placing and keeping the nutrients at the **right place** is as critical as the other factors mentioned above. As a row crop, sorghum fertilization can be done either, but not limited to, by broadcasting prior planting or banding on the surface or subsurface. Some studies indicates that band application is superior to broadcast. Banding techniques can also reduce the potential for nitrate contamination of surface or groundwater. For example Das and Subbiah (1975), Rathore and Dave (1979), Singh (1976) reported yield increase of about 300-500 kg grain ha^{-1} with band applications. Moreover, a study on the fertilizer placement effects on N accumulation in different plant organs under tillage and no-tillage conditions indicated that total N accumulation at harvest, and grain and stover yields were higher with banded placement compared to broadcast, suggesting that subsurface band placement was the most effective method of supplying fertilizer N for both tillage systems (Locke and Hons, 1988). Besides that knife injected N showed higher N concentrations in leaf tissue and grain, resulting in much higher apparent N use efficiency (Lamond et al., 1991).

3. Recommendations

Pinpointing fertilizer best management practices to optimize sorghum production is a challenging task because it depends on evaluating the response of the crop to applied rates at the right time and placement across multiple soil types, locations, environmental conditions, and management expertise. In general sorghum is less N demanding compared to similar crops, nonetheless to reach satisfactory yield the correct N dose should be applied, otherwise you risk a tremendous yield reduction. Among the main practices, split N fertilizer applications during the vegetative growth stage (from the 4th to the 10th leave stage) and placement of N in surface or subsurface bands could result in increased productivity. In that way nutrient availability and crop needs are better synchronized and therefore losses to the environment reduced (higher N use efficiency). Besides that, growing sorghum in rotation with compatible crops has the potential of not only increasing the yield and reducing chemicals, but it also has positive effects on physical-chemical and biological soil properties, and therefore the potential to enhance the sustainability of the production system and economic returns. Then, considering that the definition of fertilizer best management practices designed to improve productivity taking care of environmental impacts and profitability have yet to be developed/improved for sweet and biomass sorghum production, the use/fitting of crop models could render the definition of FBMP more economic and accessible to a wide range farmers and environmental conditions.

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