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Agave for tequila and biofuels: an economic assessment and potential opportunities

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Abstract

This paper explores the economic viability of producing biofuels from *Agave* in Mexico and the potential for it to complement the production of tequila or mescal. We focus on *Agave* varieties currently being used by the tequila industry to produce two beverages, tequila and mescal, and explore the potential for biofuel production from these plants. Without competing directly with beverage production, we discuss the economic costs and benefits of converting *Agave* by-products to liquid fuel as an additional value-added product and expanding cultivation of *Agave* on available land. We find that the feedstock cost for biofuel from the Agave piña alone could be more than US\$3 L^{-1} on average. This is considerably higher than the feedstock costs of corn ethanol and sugarcane ethanol. However, there may be potential to reduce these costs with higher conversion efficiencies or by using sugar present in other parts of the plant. The costs of cellulosic biofuels using the biomass from the entire plant could be lower depending on the conversion efficiency of biomass to fuel and the additional costs of harvesting, collecting and transporting that biomass.

Keywords: Agave, *Agave tequilana* Weber variety *Blue*, biofuels, costs of production, mescal, mescal feedstocks, Mexico, tequila

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Introduction

There is growing interest in new sources of feedstocks for biofuels that can be cultivated without competing for key resources such as land and water with food crops. Agave has been grown largely for fiber and for alcoholic beverage production in the North American continent and has high sugar and cellulose content. It also has high drought resistance and water-use efficiency and can be grown on marginal lands in arid conditions (Borland *et al*., 2009; Somerville *et al*., 2010). There are at least 200 species worldwide; more than 150 can be found in Mexico (Garcia-Mendoza, 2007). The three dominant classes of Agave cultivated in Mexico due to their high sugar and cellulosic content are *Agave tequilana* Weber variety *Blue* (hereafter referred to as *A. tequilana*), Agave species for mescal production that include *Agave angustifolia* Haw, *Agave esperrima*, *Agave weberi*, *Agave potatorum* and *Agave salmiana* (Valenzuela-Zapata, 2007a, b) (hereafter referred as mescal feedstocks) and *Agave fourcroydes* (hereafter referred as henequen).

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This paper explores the economic viability of producing biofuels from Agave in Mexico and the potential for it to complement the production of tequila or mescal.

The production of tequila currently utilizes less than half of the sugar and cellulose available in the Agave plant leaving a significant amount of biomass available for other uses such as biofuels. Additionally, with the current dependence of the Agave industry on the market for tequila, it often experiences excess supply of Agave, fluctuating demand conditions and volatile prices. There has been a surplus of *A. tequilana* cores or 'piñas' since 2003, despite the fact that demand for tequila production is increasing. Piña supply outpaced demand growth by more than 30% in the same period (Consejo-Regulador-del-Tequila, 2010; SIAP-SAGARPA, 2010). In part, this could be due to the high uncertainty about both supply and demand conditions. For instance, the demand for tequila increased by 25% in 2004 and then dropped by 20% in 2009 (Consejo-Regulador-del-Tequila, 2010). This suggests that even with current land under Agave cultivation there is considerable stock of piñas in some years that could be used for fuel-grade ethanol production and that diversifying the sources of demand for Agave could lead to better management of capacity in the industry.

Furthermore, even though the land area planted in *A. tequilana* and mescal feedstocks has more than doubled during the last 20 years, the land suitable for Agave cultivation far exceeds that currently utilized. For example, in Jalisco, the main *A. tequilana* producing region, there are 1.7 million hectares of land with suitable thermal potential for this specie; these areas are free from risks of frost occurrence and have day/night temperatures that favor photosynthesis in *A. tequilana*; of this only 163 000 ha were planted in 2008 (Ruiz-Corral *et al*., 2002). Similarly, in Oaxaca, the main state for producing mescal feedstocks, there are at least 60 000 ha of suitable land; of this only 18 532 ha were planted in 2008 (Chagoya-Mendez, 2004).

Current estimates of the value of using Agave for tequila or mescal indicate that these are high valued products with tequila yielding US\$4 L^{-1} (Orozco-Martinez, 2003). This is significantly higher than the price likely to be paid to a fuel-grade ethanol producer, who must ultimately sell ethanol at a price that is competitive with gasoline. Thus, the use of Agave for biofuels is unlikely to compete with tequila; instead the potential lies in making it a valuable by-product of tequila through more efficient utilization of available plant material and in the expansion of production to currently unused available land. In addition, henequen offers another source of biomass for biofuel that is compatible with current fiber production practices.

The second section of this paper provides a brief background of Agave cultivation practices and methods of producing tequila, mescal and henequen production in Mexico. The third section presents production and cost analysis based on the information available for *A. tequilana* and mescal feedstock. We were unable to find reliable estimates of the costs of producing henequen and therefore do not discuss those here. The fourth section describes the potential costs of using Agave for biofuel production and identifies the gaps in the data needed for complete assessment of its economic viability. The fifth section explores the economic potential of Agave-based biofuels and the gaps in the technical and economic information available to undertake a more comprehensive assessment and the sixth section concludes.

Background

This section briefly describes the current state of Agave production, cultivation practices for each species and methods of producing tequila, mescal and fiber in Mexico. Figure 1 shows the areas planted under the three Agave species in the period 1995–2008. At the end of twentieth century, henequen occupied more agricultural land than the other two species, but since 2000 area planted under *A. tequilana* has grown at high rates; in 2008, it became four times more than under henequen and mescal feedstocks. In the next section, we provide further details for each of the three species.

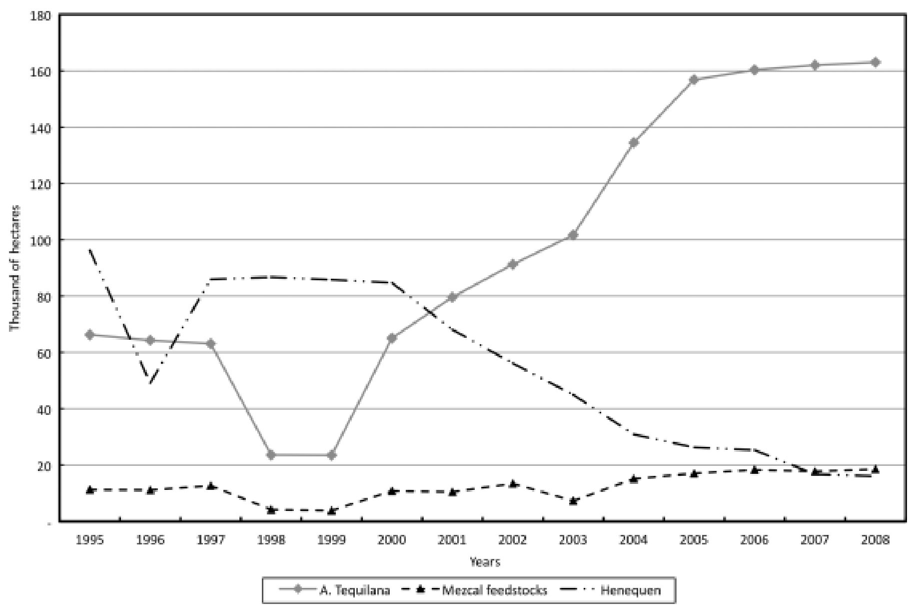

Fig. 1 Area planted under *Agave tequilana*, mescal feedstocks and henequen in thousands of hectares 1995–2008. Source: SIAP-SAGARPA (2010). Note: Henequen area corresponds only to Yucatan.

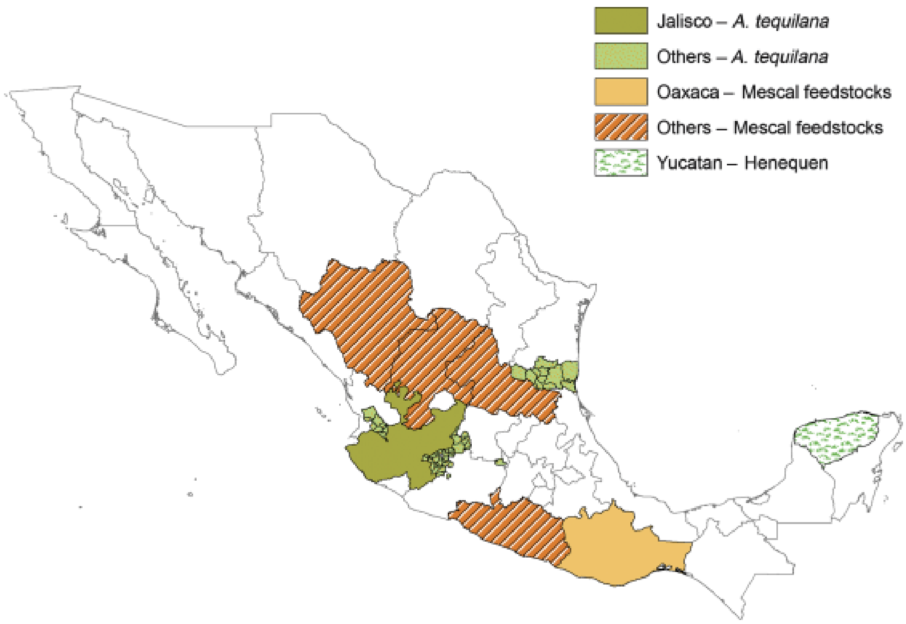

Fig. 2 Main producing regions of Agave in Mexico. Map by the authors.

Agave tequilana and tequila production

According to the Protected Geographic Status for Tequila (Denominación de Origen Tequila; DOT), tequila '100% Agave' must be produced from *A. tequilana* Weber Blue only in the state of Jalisco and some municipalities in the states of Guanajuato, Nayarit, Michoacán and Tamaulipas (Consejo-Regulador-del-Tequila, 2010) (see Fig. 2). In 2008, 74% of the total area planted and 84% of the total *A. tequilana* production in Mexico occurred in Jalisco. The heterogeneity in yields across the states within this region can be seen in Fig. 3. *A. tequilana* is usually planted on hills and stony light soils characterized by high content of oxides and potassium, good drainage and high exposure to sunlight (SIAP, 2010). It is a perennial crop that has at least a 6-year life cycle before harvest, in addition to time required for plant propagation which could entail a full year. Plants are harvested individually when the piña reaches optimum levels of size and sugar content. Thus, a field of *A. tequilana* can be harvested progressively for a period of up to 2 years.

The areas where *A. tequilana* is planted has increased significantly from 1999 to 2004, after which it leveled off (Fig. 1). In 2008, there were 163 000 ha planted with 3000–3300 Agave plants ha^{-1} on average. Of these only 14 332 ha were harvested, producing 1 493 287 metric tons (Mg, fresh weight) of piñas for tequila production (SIAP-SAGARPA, 2010).

The level of production of *A. tequilana* in thousands of Mg of piñas and the real value of this production in millions of dollars in 2007 prices are shown in Fig. 4 (We use the National Producers Price Index reported by Banco-de-Mexico (2010) to convert the value of production into 2007 prices. The value of production is the average price per Mg received by farmers at the farm gate times the total production.). The drop in the total

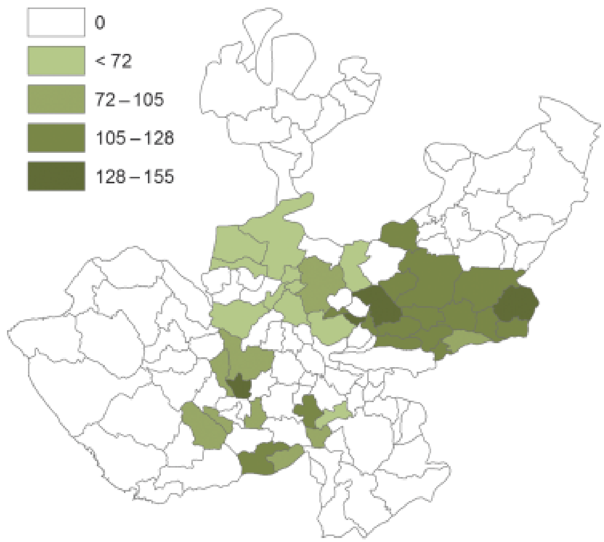

Fig. 3 Yields ($Mg\,ha^{-1}$) of *Agave tequilana* in Jalisco, Mexico in 2008. Note: These yields are obtained with a 5–7 year life cycle of the plant. Yields ($Mg\,ha^{-1}\,yr^{-1}$) will vary depending on share of the land harvested and rotated each year. Source: SIAP-SAGARPA (2010). Map by the authors.

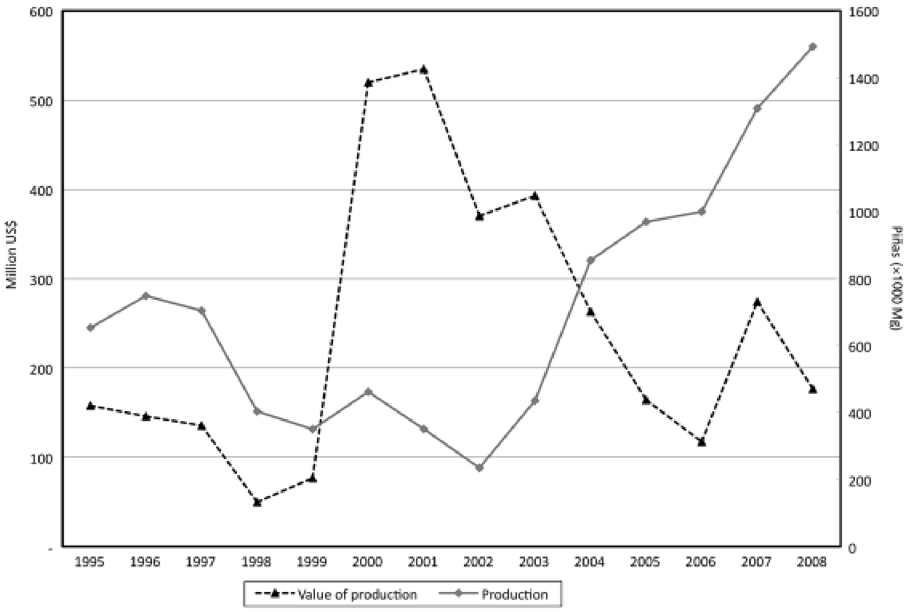

Fig. 4 Value and level of production of *Agave tequilana* in Mexico 1995–2008. Source: SIAP-SAGARPA (2010). Value is in 2007 prices and converted to US$ using 2007 exchange rate of US$ 1 to MXN10.9 (Banco-de-Mexico, 2010).

value after 2003 is due to the low price of Agave in those years given an oversupply of piñas. Macias-Macias and Valenzuela-Zapata (2009) suggest that the gaps between demand and supply are due to a lack coordinated planning between tequila industry and independent Agave producers. As a result producers need to plant for an uncertain demand in 5–7 years, when the plants will be ready for harvest. While much of the Agave production occurs on plantations owned and managed by, or under contract with tequila processors, about 20% of production is by independent farmers (Leclert, 2007).

Cultivation, harvest and tequila production. Agave bulbs are propagated in a protected environment (i.e. shadehouse or greenhouse), hardened and classified; after a year 'young plants' are ready for planting. *A. tequilana* cultivation starts with tilling the land at the beginning of the rainy season. The planting task can be mechanized, depending on the topography of the soil – although for most part this is a manual task. Young plants are planted in the plowed land and new root growth can be observed immediately (Kelly, 2009; Davis *et al.*, 2011). At the beginning of the second year replanting occurs to replace failed plants. In general, this amounts to between 4% and 10% of plants. Every year land is plowed and the leaves are pruned leaving only those that surround the piña to encourage growth.

After the original planting, this crop takes at least 6 years before piñas can be harvested; during this time it needs periodic maintenance, such as:

- removal of weeds to avoid competition for nutrients, sunlight and water,
- loosening of the soil around the plant to facilitate establishment and development of young plants,
- fertilizer application and additional pests and diseases control.

Maintenance activities may be performed with the assistance of livestock (oxen) or a tractor with additional pruning of the side leaves required allowing space for the tractor (or oxen). Before the harvesting season, when the stem of the plant shows up, it has to be trimmed to increase sugar content and the size of the piña. After the sixth year, harvesting or 'jimado' is performed with plants selected individually depending on the maturity of the piña – or when the piña has a sugar content of at least 24°Bx (24 g of sucrose in 100 g of solution). At that time, the leaves are trimmed and the piña is severed from the root, leaving the piña fully exposed. Leaves and other parts of the plant are generally abandoned on the land, which then form an organic layer on the soil. The piñas are transported to the tequila facilities. After harvesting and before a new planting season, the land is generally left fallow for 1 year (Cedeño-Cruz & Alvarez-Jacobs, 1999; Valenzuela-Zapata, 2007a, b; SIAP, 2010).

The piñas in the tequila factories are quartered or halved, baked in stone or brick ovens, stainless-steel autoclaves, or diffusers for hydrolysis for 30–72 h and later allowed to stand for 12–36 h. Extraction of the sugar is completed by crushing the cooked piñas to separate the sugar-rich pulp from the bagasse. The sugar-rich pulp is sent to fermentation and distillation. The extracted pulp is fermented with yeast and finally copper stills are used for the distillation process. Vinasse is the residue that remains after the distillation process, and contains mainly nonfermentable dissolved organic matter, which could be digested to methane (see Davis *et al*., 2011 for details). Currently, vinasse is often land applied. A fibre-rich bagasse remains after depulping, as in the cane-to-ethanol process, which is commonly used as a fuel for electricity generation; conceivably this may be an option with *A. tequilana* feedstock as well. Currently; however, this residue is composted and reapplied to the fields as a mulch and fertilizer. A third alternative may be to utilize this fiber-rich bagasse in a cellulose-to-ethanol process.

Estimates of the amount of *A. tequilana* required to produce 1 L of tequila (40%–55% alcohol by volume) range from 5.5 to 8 kg. Before bottling, tequila is stored in wooden barrels. In 2008, the Mexican tequila industry had the capacity to process 900 000 Mg of Agave to produce 350 million liters of tequila (Camara-Nacional-de-la-Industria-Tequilera, 2008). This is much smaller than the amount of Agave production in 2008 (Fig. 4). This suggests that limited demand for tequila is a key reason for the dramatic drop in the price of Agave.

The mass of the piña of *A. tequilana* ranges from 20 to 60 kg; concentrated sugars constitute 27% of wet mass whereas cellulose constitutes 40% of the wet mass (Cedeño-Cruz & Alvarez-Jacobs, 1999; Iñiguez-Covarrubias *et al*., 2001b). Additionally, *A. tequilana* leaves, which on average represent 29% of the total weight of the plant, have a sugar content of 13–16%, a cellulose content of about 65%, lignin of 16% and hemicelluloses of 5% (Iñiguez-Covarrubias *et al*., 2001a; Sanjuan *et al*., 2010). Finally, the bagasse obtained after crushing the piña is about 40% of the total mass of the piña and has a high cellulose (20–50%), hemicellulose (19%), lignin (15%) and total soluble sugar (5%) content (Cedeño-Cruz & Alvarez-Jacobs, 1999; Iñiguez-Covarrubias *et al*., 2001b; Alva Munoz & Riley, 2008; Sanjuan *et al*., 2010).

Mescal feedstocks and mescal production

Mescal feedstocks are used to produce mescal, a popular alcoholic beverage. The production process is similar to that of tequila but at least 25 different Agave species can be used to produce mescal (Chagoya-Mendez, 2004). Under the Protected Geographic Status for Mescal (Denominación de Origen Mescal, DOM), it can only be produced in the states of Oaxaca, Zacatecas, Guerrero, San Luis Potosí, Durango and some municipalities in the states of Tamaulipas and Guanajuato (See Fig. 2). In 2008, Oaxaca planted 86% and produced 89% of the total mescal feedstocks in Mexico (SIAP-SAGARPA, 2010). The most commonly grown mescal variety is *A. angustifolia* Haw, which accounted for more than 60% of total production (Chagoya-Mendez, 2004).

The yield (Mg ha^{-1}) of the mescal piñas is historically much lower than *A. tequilana* as shown in Fig. 5 for the period 1995–2008 and varies across locations (Fig. 6). Although the fresh weight yield ranged from 50 to 70 Mg ha^{-1}, the fresh weight yield of piñas of *A. tequilana* varied between 100 and 142 Mg ha^{-1} in 2008. These yields are obtained from a harvest in year 5–8, thus average annual yields, wet weight, range between 6–14 Mg ha^{-1} yr^{-1} for mescal feedstocks and 12–28 Mg ha^{-1} yr^{-1} for *A. tequilana* in 2008.

Again, only the piña is used for the mescal production and the rest of the plant and by-products could be available for biofuel production. For instance, in the case of *A. salmiana*, leaves represent more than 50% of the total weight of the plant (Garcia & Romero, 2010) and leaves have a similar cellulose content as that of *A. tequilana* (Cuevas-Figueroa & Flores-Berrios, 2006; Vargas-Ponce *et al*., 2009).

There are few reliable estimates of demand for mescal feedstocks because a significant part of the production is used for local consumption. According to Consejo Regulador de la Calidad del Mezcal (2008), there were 269 legal producers of mescal in 2008 and they produced about 1.8 million liters. This implies a demand of 16 000–21 000 Mg of mescal feedstocks assuming a conversion rate ranging between 83 and 111 L Mg^{-1} of mescal. The reported production of piñas for mescal in 2008 was about 301 000 Mg (Fig. 7) (SIAP-SAGARPA, 2010). Even assuming that a substantial part of this is consumed locally, it would potentially leave a significant stock of mescal feedstocks available for biofuel production.

The area planted under the mescal feedstocks has not increased as much as that under *A. tequilana*, but it did increase 155% from 2003 to 2008 (Fig. 1) (SIAP-SAGARPA, 2010). The total value of production has remained very low since 2004 because of low prices (Fig. 7) (SIAP-SAGARPA, 2010). Again, this could reflect a decrease in the demand from the tequila industry and the lack of strategic planning between mescal feedstocks and the mescal industry (Chagoya-Mendez, 2004). In 2008, there were 18 532 ha planted (Fig. 1) and 4701 ha were harvested. It is interesting to note that this harvesting rate

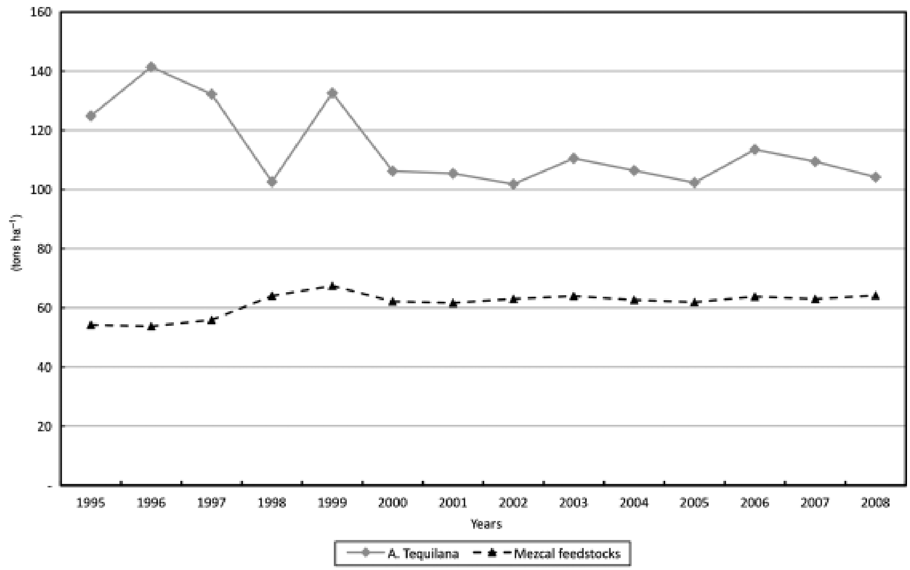

Fig. 5 Yields of *Agave tequilana* and mescal feedstocks in Mexico 1995–2008. Source: SIAP-SAGARPA (2010).

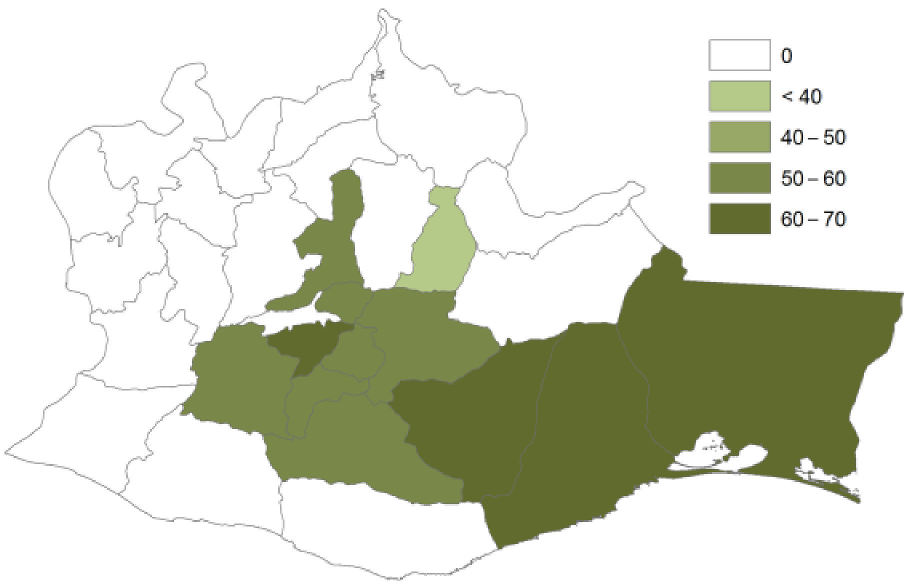

Fig. 6 Yields (Mg ha^{-1}) of mescal feedstocks in Oaxaca, Mexico in 2008. Note: These yields are obtained with a 6–8 year life cycle of the plant. Yields (Mg ha^{-1} yr^{-1}) will vary depending on share of the land harvested and rotated each year. Source: SIAP-SAGARPA (2010). Map by the authors.

is higher than that for *A. tequilana*, despite the fact that areas planted and yields under *A. tequilana* are much higher. Total production was 301 791 Mg and the total value received by farmers was US$33.2 million (Fig. 7) (SIAP-SAGARPA, 2010).

Cultivation, harvest and mescal production. The mescal varieties of Agave are also perennial crops and take more than 6 years of production before harvesting. Most of cultivation methods are similar to those for *A. tequilana*, although they are more labor intensive. Two types of cultivation practices are typically used: intensive and semi-intensive (Chagoya-Mendez, 2004). The intensive practice is used in areas with steep slopes, unsuitable for mechanization. Planting density is high, ranging from 2000 to 4500 plants ha^{-1} (Chagoya-

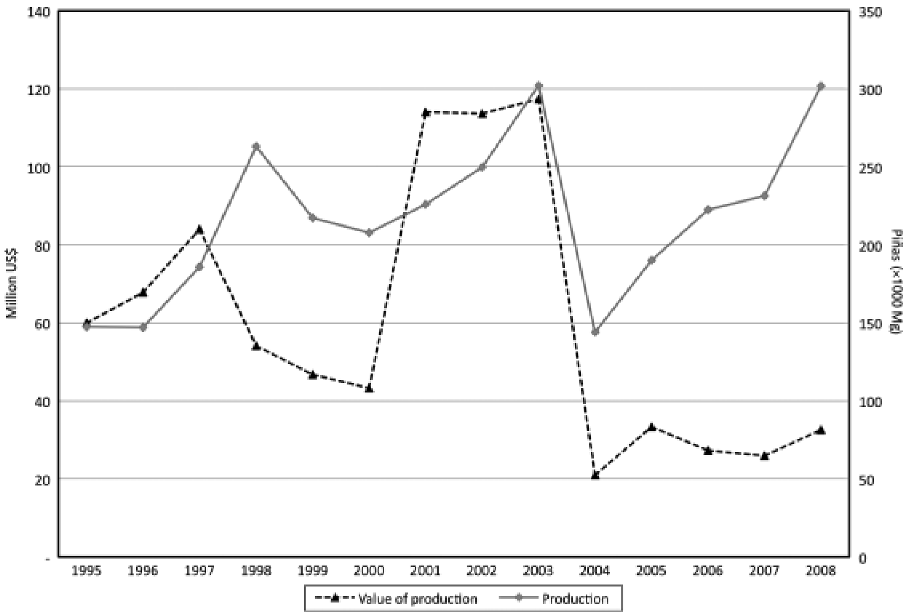

Fig. 7 Value and level of production of mescal feedstocks in Mexico 1995–2008. Source: SIAP-SAGARPA (2010). Value is in 2007 prices and converted to US$ using 2007 exchange rate of US$ 1 = MXN10.9 (Banco-de-Mexico, 2010).

Mendez, 2004). With this practice, it takes on average 8 years for the plant to be ready for harvest. This practice is utilized on about 80% of the area planted with mescal feedstocks and accounts for nearly 90% of the total production in Oaxaca, particularly in the districts of Tlacolula and Yautepec (Fundacion-Produce-Oaxaca, 2004). Maintenance and harvesting activities are quite similar to those of *A. tequilana*, but more labor intensive. After harvest, the field is left to rest. The fallow could be as long as 3–6 years and after this time the production cycle starts again (Chagoya-Mendez, 2004).

Semi-intensive practices are largely used on less steep hills and less stony fields, which are more amenable to mechanization. Planting densities are < 2500 plants ha^{-1} (Chagoya-Mendez, 2004). This is possibly because semi-intensive practices are used on lands that are also suitable for planting other crops; subsistence crops such as beans, corn and squash are typically planted in the furrows between the rows after *Agave* is planted. With this practice, it takes a plant 7 years after planting to be ready for harvest. The rest of the cultivation and harvesting processes are similar to those for *A. tequilana*.

The mescal industry uses less technology and equipment than the tequila industry. After the piñas are taken to the mescal factories they are cut and baked in earthen ovens with a capacity of 3–7 Mg. These ovens are generally heated with firewood and juice is extracted from the piñas using roller mills powered by livestock traction. Clay or copper stills are used for the distillation process. One liter of mescal requires between 9 and 12 kg of piña. Before bottling, mescal is generally stored in plastic containers (Chagoya-Mendez, 2004). The properties of a piña of mescal feedstocks are similar to those of *A. tequilana* (Cuevas-Figueroa & Flores-Berrios, 2006; Maldonado-Sanchez, 2009; Vargas-Ponce *et al.*, 2009; Nobel, 2010).

Henequen and fiber

Fiber from henequen is the third main product made from the Agave in Mexico. Only the leaves are utilized for making fiber. As in mescal and tequila, many parts of the plant are unused by-products like the juice from the leaves and, notably, the piña. According to Zumalacarregui (2010) only 3–4% of the plant is used effectively for fiber production, and the remainder could be used for ethanol production. Henequen piña mass is between 9 and 19 kg and has a high cellulose and sugar content, providing a juice yield of approximately 3 L piña^{-1} (Rendon-Salcido *et al.*, 2009; Larque-Saavedra *et al.*, 2010).

Acreage under henequen has dropped from 260 000 ha in 1981 to 18 000 ha in 2008; the drop has been particularly steep since 2001. Henequen is planted mainly in the state of Yucatan (See Fig. 2); in 2008, 89% of all henequen produced in Mexico was planted there (SIAP-SAGARPA, 2010). Area planted was 16 000 ha (with 2000–4000 plants ha^{-1}) in 2008 (see Fig. 1). Biofuel production provides an opportunity for henequen to expand, with more than 200 000 ha of land that have

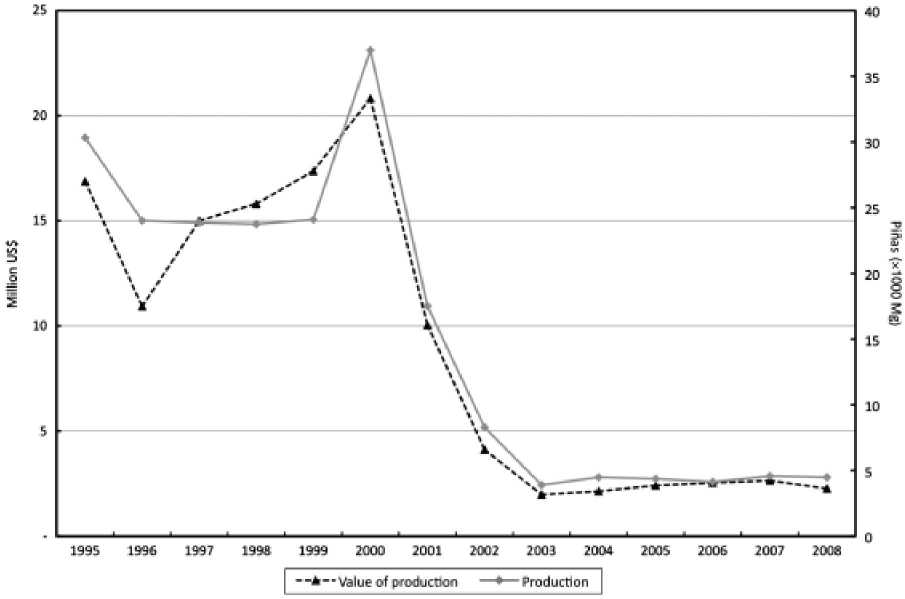

Fig. 8 Value and level of production of henequen in Yucatan, Mexico 1995–2008. Source: SIAP-SAGARPA (2010). Value is in 2007 prices and converted to US$ using 2007 exchange rate of US$ 1 = MXN10.9 (Banco-de-Mexico, 2010).

been used at least once for henequen and are suitable and available for expanding production. Henequen production has fallen during the same period from 43 100 to 10 500 Mg (Fig. 8) (SIAP-SAGARPA, 2010). This has primarily been caused by low demand for henequen fibers due to substitution by synthetic fibers (Nobel, 2010). This drop in the demand for henequen has gone hand in hand with a fall in its price (Fig. 8). In 2008, in Yucatan, 9036 ha were harvested for fiber. The amount harvested was 4487 Mg of leaves with a value of US$2.5 million.

Cultivation, harvest and fiber production. Henequen is also a perennial crop that takes more than 6 years before it can be harvested, depending on the amount, quality, and size of the leaves. Henequen cultivation practices are highly labor intensive with very little mechanization. After propagation, hardening and classification, henequen can be planted in highly volcanic and clay soil, porous and abundant in iron and in elements derived from basalt. Cleaning and fertilizer application activities are carried out periodically from the first year onwards. After the sixth year, harvesting is done by cutting the more mature leaves close to the stem; this is repeated periodically until the plant has reached maturity. This manner of cultivation causes the stem to elongate, which by then is covered with white flowers ('quiote'). About 25–30 leaves can be obtained from each harvest and the life cycle of henequen is about 14–20 years (Fox, 1961; Payno & Rosen Jelomer, 2005; SIAP, 2010). The leaves are bundled and sent to an extraction process to recover the fiber, which is only a small fraction of the leaf. Currently, this fiber goes directly to market and use, however it may similarly be useful for deconstruction in cellulosic ethanol production and/or combustion for electricity production and/or composting.

After harvesting, leaves must be processed within the next 24 h to be able to clean the fiber properly. A decorticating mill is used to extract the fiber from the leaf, while it is constantly washed with water. Here juice and pulp of the leaves are generated as by-products. Fiber is dried in the sun or by steam. The dried fiber is classified depending on length, cleanliness, and moisture. Finally, fiber is baled and transported to the market (Fox, 1961; Otero-Baña, 1999).

The properties of the leaves of henequen include a cellulosic content of about 78%, hemicelluloses of about 6%, and lignin about 13% (Davis *et al.*, 2011). Additionally, some of the properties of the piña are a sugar concentration varying between 9 and 17°Bx and a cellulose content of about 60% (Rendon-Salcido *et al.*, 2009; Larque-Saavedra *et al.*, 2010).

Costs and returns from production of Agave

Detailed information related to Agave production costs is scarce because of the high heterogeneity in the technology, soils, land property, and the varying production practices. Furthermore, since Agave is at least a 6-year crop, maintenance and cultivation practices can change every year depending on factors such as weather, crop diseases, input and labor costs and Agave prices. Given this heterogeneity, the cost estimates presented here are approximate numbers based primarily on *Agave* local governments reports from each of the main producing states (Chagoya-Mendez, 2004; SAGARPA, 2004).

Tables 1–3 report the annual costs for *A. tequilana* and for mescal feedstocks under both intensive and semi-intensive practices by field operations. Annual maintenance is the most costly activity for mescal feedstocks and annual chemical input application is the most costly activity for *A. tequilana*. Maintenance costs include the costs of replacing failed plants and of extracting offshoots. Additionally, trimming of the leaves is done periodically to encourage the piña to grow and to facilitate tillage.

Likewise, depending on the soil conditions and weight and sugar content in the piña, fertilizer application must be carried out periodically. Fertilizers include manure, lime, ammonium, potassium among others. The amount applied ranges between 0.5 and 2 kg plant^{-1} depending on the growth stage. Some farmers use herbicide applications, mainly Glyphosate, to remove weeds. Agave can be attractive to several pests. Farmers use different methods to combat their effects. These include chemical applications, hand-pulling and cultivation methods to prevent and/or kill bacteria such as *Erwinia* sp ('Secazón'), fungi such as *Fusarium* ('Anillo rojo' or 'Gomosis') and *Colletotrichum agavis* ('Antracnosis'), pests such as *Scyphoporus interstitialis* Gyllenhal ('Picudo'), *Strategus* sp ('Toro'), *Aspidiotus* sp ('Escamas') and *Hypopta agavis* ('Gusano Rojo') (Chagoya-Mendez, 2004).

We first tabulate the costs of establishment, maintenance and harvesting for both *A. tequilana* and mescal feedstocks. We then discuss other costs such as land and management costs. Using estimates provided in SAGARPA (2004), we find that the production of *A. tequilana* is very labor intensive and requires chemical inputs (Table 1). While costs associated with establishment and planting are high in the first year, maintenance and labor costs are high subsequently. Overall the cost per hectare is uniformly distributed over the life of the plant, with the exception of the last year when harvesting costs result in total costs per hectare double that of previous years. Inputs such as plants, chemicals, fertilizers and tools constitute about 56% of the total costs over the life of the plant, followed by the cost of labor hired which is about 37% of total costs. The share of machinery in total cost is only 4%. These costs correspond to an average 7-year crop (1997–2003) with 3150 Agave plants ha^{-1}. The labor cost is higher in the last year since harvest workers ('jimadores') are added to the workforce and they spend considerable time selecting and cutting plants.

The production of mescal feedstocks using intensive practices with 3300 plants ha^{-1} is a highly labor intensive activity (Table 2). The main costs are those of the plants and their annual maintenance with a small amount of fertilizer application in the first 4 years. In the last 3 years of the plant's life cycle, there are costs associated with harvesting. Overall, the costs are highest in the first year when the plants are established and in the seventh–eighth year when the bulk of the harvesting is carried out. With an 8-year harvesting cycle, the share of the cost of hired labor is about 77% of the total cost of producing the crop over its life cycle (Chagoya-Mendez, 2004). There are no machinery costs since these lands are not amenable to mechanization.

In the case of mescal feedstocks grown using the semi-intensive practice with a 7-year harvesting cycle and 2150 plants ha^{-1}, the cost of production is twice as high in the establishment year as compared with sub-

Table 1 Annual costs of production of *Agave tequilana* (US$) (3150 plants ha^{-1})

	Year						
Item	1997	1998	1999	2000	2001	2002	2003
Land preparation	296	0	0	0	0	0	0
Plants	292	32	0	0	0	0	0
Planting	117	13	0	0	0	0	0
Transportation of plants and inputs	308	16	0	0	0	0	0
Maintenance (labor)	236	458	542	542	542	542	542
Fertilizers and chemicals	385	603	691	1201	1201	1201	1201
Harvesting	0	0	0	0	0	0	1750
Total per year (US$ha^{-1})	1634	1122	1233	1743	1743	1743	3493

Exchange rate is US$1 = MXN10.8 in 2003 (Banco-de-Mexico, 2010).
Source: SAGARPA (2004).

Table 2 Annual costs of production of mescal feedstocks using intensive practice (US$) (3300 plants ha^{-1})

	Year							
Item	1996	1997	1998	1999	2000	2001	2002	2003
Land preparation	278	0	0	0	0	0	0	0
Plants	1222	61	0	0	0	0	0	0
Planting	102	9	0	0	0	0	0	0
Transportation of plants and inputs	46	19	0	0	0	0	0	0
Maintenance (labor)	1278	657	889	889	1565	0	0	0
Fertilizers and chemicals	46	46	46	46	0	0	0	0
Harvesting	0	0	0	0	0	74	1481	481
Total per year (US$ha^{-1})	2972	792	935	935	1565	74	1481	481

Exchange rate is US$1 = MXN10.8 in 2003 (Banco-de-Mexico, 2010).
Source: Chagoya-Mendez (2004).

Table 3 Annual costs of production of mescal feedstocks using semi-intensive practice (US$) (2250 plants ha^{-1})

	Year						
Item	1997	1998	1999	2000	2001	2002	2003
Land preparation	176	0	0	0	0	0	0
Plants	625	31	0	0	0	0	0
Planting	150	8	0	0	0	0	0
Transportation of plants and inputs	9	19	19	19	19	19	0
Maintenance (labor)	204	324	352	444	491	269	130
Fertilizers and chemicals	194	303	235	244	244	105	0
Harvesting	0	0	0	0	0	0	602
Total per year (US$ha^{-1})	1358	685	606	707	754	393	732

Exchange rate is US$1 = MXN10.8 in 2003 (Banco-de-Mexico, 2010).
Source: Chagoya-Mendez (2004).

sequent years in the plant's life cycle (Table 3). Maintenance and fertilizer costs are high in years 2–6 and harvesting costs are the major cost item in the seventh year. Hired labor constitutes 46% of total costs, but inputs such as chemical and fertilizers also have a relatively high share (39%). Although not shown explicitly, the share of machinery for preparing the land and for maintenance is about 12% of the total cost, which is higher than for *A. tequilana*.

The annual costs in Tables 1–3 are converted to present value in constant US dollars in 2003 prices using National Producers Price Index and a real interest rate of 4%, which is close to the real rate of interest in Mexico over the period from 1997 to 2003 (Banco-de-Mexico, 2010). A summary of the total costs of production, the yield of the plant and the price received by the farmer and the distillery is provided in Table 4. With 3150 plants ha^{-1} and each plant yielding a piña with a weight of about 30 kg, it is estimated that the yield of *A. tequilana* is 94.5 Mg ha^{-1} (SAGARPA, 2004). The average yield harvested between 1997 and 2008 has been close to 100 Mg ha^{-1}. In the case of mescal feedstocks, the yields implied by the planting rate in Tables 2 and 3 and the assumption that the weight of each piña is 50 kg with the intensive practice and 60 kg with the semi-intensive practice are 165 and 135 Mg ha^{-1}, respectively (Chagoya-Mendez, 2004). Harvested yields (Mg ha^{-1}) indicated in Fig. 5 are much lower and have ranged close to 60 Mg ha^{-1}, possibly because of lower piña weights or because all plants were not harvested. We use estimates of the average harvested yield to determine the cost per megagram. All costs are reported in US dollars in 2003 prices.

Thus, the cost of producing Agave is US$180 Mg^{-1} for mescal feedstocks using semi-intensive practices and US$212 Mg^{-1} using intensive practices. The cost of producing *A. tequilana* is US$162 Mg^{-1}. The average price received by the Agave farmer is US$364 Mg^{-1} for *A. tequilana* and about half of that (US$191 Mg^{-1}) for mescal feedstocks over the period 2003–2005. The

Table 4 Costs of production and revenue of Agave in constant US$ in 2003 prices

			Mescal feedstocks	
Item		Tequilana	Intensive	Semi-intensive
Present value of cumulative cost (US$ha^{-1})*,†		17 240.9	16 104.5	9158.5
Yield with a single harvest (Mgha^{-1})‡		106.0	76.0	51.0
Present value of the cost (US$ Mg^{-1})*	a	162.6	211.9	179.6
Average price received by Agave farmers (US$Mg^{-1})*,‡	b	364.5	191.1	191.1
Margin of Agave farmers (US$Mg^{-1})	$b-a$	201.9	−20.8	11.5
Yield (L Mg^{-1})†,§	c	125–182	83–111	
Feedstock cost of Agave for tequila/mescal (US$ L^{-1})	$d=b/c$	2.0–2.9	1.7–2.3	
Price received for tequila or mescal by distillers (US$ L^{-1})¶	e	3.8	3.7	
Margin of tequila/mescal distilleries (US$ L^{-1})	$e-d$	0.9–1.8	1.4–2.0	

*Costs are in 2003 prices. Rate of interest is assumed to be 4%. Exchange rate is US$1 = MXN10.8 in 2003 (Banco-de-Mexico, 2010). Average 2003–2005 price received by Agave farmers.
†SAGARPA (2004) and Chagoya-Mendez (2004).
‡SIAP-SAGARPA (2010).
§Davis *et al*. (2011).
¶Orozco-Martinez (2003) and Chagoya-Mendez (2004).

margin for the *Agave* farmer was therefore US$202 Mg^{-1} for *A. tequilana* and less than US$12 Mg^{-1} for mescal feedstocks. It has to be noted that there is high uncertainty about the net returns, which change significantly year to year because of the high variability in the price of *Agave*, as shown in Figs 5 and 8. In the case of mescal feedstocks grown using the intensive practice, Table 4 shows a negative margin given the average price in the period 2003–2005. These returns would have been positive in 2002 due to the high price that year (US$337 Mg^{-1}). Thus, farmers may have planted these feedstocks in the expectation of positive profits but had to sell the crop when prices were low, resulting in a loss. Despite the lower profitability of intensive cultivation practices relative to the semi-intensive practice, indicated in Table 4, adoption of the intensive practice may represent the best use of that land given its terrain.

The margin between costs and prices above should cover rent or returns to the land, taxes, management and other costs. According to SAGARPA (2004), *A. tequilana* farmers might pay between US$330 and US$440 as land rent per hectare per year, about US$30 ha^{-1} yr^{-1} for taxes on land, around US$330 ha^{-1} for management costs and US$50 Mg^{-1} on average for transportation of the piñas to the factory. Transportation costs are significant since distilleries may be located far from the fields; these costs are usually paid by a third party who then charges the tequila producer. If we add these, the costs for *A. tequilana* Mg^{-1} are an additional US$90 Mg^{-1}. This suggests that if the price of *A. tequilana* was as low as that in 2006 (Fig. 4), farmers would not be able to cover their costs of production as noted by Macias-Macias and Valenzuela-Zapata (2009). It is also possible for farmers to get additional income from selling the 'young plants' or shoots to the nurseries; this price ranges between US$0.2 and US$0.9 per shoot depending on the market condition in a given year. On the other hand, transportation costs for the piñas of mescal feedstock were about US$10 Mg^{-1}, which are lower than those for *A. tequilana* because more than 40% of the farmers are also the producers of mescal leading to very low transportation costs as the oven is near the crop (Chagoya-Mendez, 2004).

In the case of henequen, SIAP-SAGARPA (2010) reports yields of about 0.5 Mg ha^{-1} and the prices paid in recent years ranged between US$350 and US$550 Mg^{-1}. Magdub-Méndez (2010) indicates that henequen production costs are about US$135 Mg^{-1}.

We can use the information about the price of *A. tequilana* and mescal feedstocks and the price of tequila and mescal to infer the returns to the distilleries. The amount of tequila produced from *Agave* ranges between 125 and 182 L Mg^{-1} whereas the amount of mescal produced from Agave ranges between 83 and 111 Mg^{-1}. The price paid to tequila producers was about US$3.8 L^{-1} of tequila '100% Agave' in 2004 (Orozco-Martinez, 2003), whereas that of mescal was US$3.7 L^{-1} (Chagoya-Mendez, 2004). This implies a margin of US$0.9–US$1.8 L^{-1} for tequila producers and US$1.4–US$2.0 L^{-1} for mescal producers without considering capital costs, transportation, costs, taxes and profits.

Potential costs of biofuels from Agave

As mentioned above, tequila and mescal production processes use only about 62% of the Agave piña. Other parts of the plant, such as roots and leaves, and by-products, such as the bagasse and vinasse, are currently not used. Those parts of the plant represent almost 50% of the plant weight and have high cellulose and sugar content (Cedeño-Cruz & Alvarez-Jacobs, 1999; Iñiguez-Covarrubias *et al.*, 2001a; Borland *et al.*, 2009; Sanjuan *et al.*, 2010). Several recent investigations (Maldonado-Sanchez, 2009; Madrigal Lugo & Velazquez Loera, 2010; Velez Jimenez, 2010; Davis *et al.*, 2011) indicate that the conversion efficiency of biofuel production from piñas is similar to that for tequila/mescal production, that is, 0.4–0.55 L of biofuel 5.5–8 kg^{-1} of piñas, once excess water has been removed to achieve fuel grade standards. This implies that the feedstock costs for biofuel from the piña would be about US\$3.1–3.6 L^{-1} of biofuel on average (Table 5). This approach to converting piñas alone to biofuels would therefore result in very high costs of biofuels. To be economically viable much higher conversion efficiencies would be required or conversion of a larger portion of biomass to fuel would be required. A conversion efficiency that is similar to that for the current corn ethanol production process and yields of 417 L Mg^{-1} of corn (as in Davis *et al.*, 2011) could reduce the feedstock cost for Agave-based biofuels to US\$0.5–US\$0.9 L^{-1} (Table 5). Even with this rate of conversion, these feedstock costs per liter of biofuel are much higher than the feedstock costs of corn ethanol in the United States and sugarcane ethanol in Brazil. These are estimated to be US\$0.34 and US\$0.23 L^{-1}, respectively, in 2007 prices (Crago *et al.*, 2010). Maldonado-Sanchez (2009) estimates an ethanol production cost of US\$0.13 L^{-1} from the piña of mescal feedstocks. In part this low cost is due to the very high yield assumed, i.e. 525 Mg ha^{-1}, which would come from an 'improved Agave' variety and due to a low total cost also, i.e. US\$8655 ha^{-1}. These estimates do not appear to include all the costs of maintenance of the Agave field and the cost of land. More research is needed on the potential to improve the yields of Agave varieties grown for biofuels and to improve the efficiency of converting the feedstock into biofuels.

A few studies have examined the properties of the *Agave* leaves and their potential for use in biofuel production. Cáceres-Farfán *et al.* (2008) and Magdub-Méndez (2010) find that ethanol production is possible by using the juice extracted from the henequen leaves during the process of fiber production 'diluted to 8–10°Br together with molasses up to 12°Br' from the sugar industry. They estimate that from every Mg of henequen leaves it is possible to obtain 50 kg of fiber and 40 L of ethanol. Magdub-Méndez (2010) consider it possible to produce biofuels at a cost of US\$0.4 L^{-1} from henequen leaves.

Table 5 Potential Feedstock Costs for Biofuels

Item	Tequilana	Mescalero
Average price received by Agave farmers (2003–2005) (US\$ Mg^{-1})*	364.5	191.1
Biofuel yield from sugar assuming similar conversion efficiency as for tequila/mescal (L Mg^{-1} of piñas)†,‡	100.0	61.1
Feedstock cost of biofuel from piñas (US\$ L^{-1})	3.6	3.1
Biofuel yield from sugar assuming conversion efficiency of corn ethanol (L Mg^{-1} of piñas)‡	417.0	417.0
Potential feedstock cost of biofuel from piñas (US\$ L^{-1})	0.9	0.5
Cellulosic biofuel yield assuming conversion efficiency of cellulosic fuel (L Mg^{-1} of piñas)§	330.0	330.0
Feedstock cost of cellulosic ethanol (US\$ L^{-1})¶	0.6	0.3

*SIAP-SAGARPA (2010), constant US\$ in 2003 prices.

†Chagoya-Mendez (2004). These yields are based on the assumption that it is possible to obtain 0.55 L of biofuel from 5.5 kg of piñas from A. tequilana and from 9 kg of piñas from mescal feedstocks, once excess water has been removed to achieve fuel grade standards.

‡Davis *et al.* (2011).

§Wallace *et al.* (2005).

¶These costs are based on the assumption that the yield of Agave biomass is twice the yield of the piñas, i.e. 212 Mg ha^{-1} for *A. tequilana* and 126 Mg ha^{-1} for mescal feedstocks.

If *Agave* is grown exclusively for biofuel production and the entire Agave plant is a feedstock for cellulosic biofuels the biomass yield (Mg ha^{-1}) could be twice that of the piña alone (i.e., 126–212 Mg ha^{-1}). Using our estimates of the price of *Agave* and assuming a conversion efficiency of cellulosic fuel of 330 L Mg^{-1} (Wallace *et al.*, 2005), the feedstock cost for Agave-based biofuels would drop to US\$0.3–US\$0.6 L^{-1} (Table 5). These costs could be higher if additional costs of harvest and transportation for the rest of the plant are included.

On the other hand, if biofuel production is a by-product of the use of Agave for beverage production, then the costs of the cellulosic feedstock will only be the incremental costs of harvesting, collecting and transporting the biomass. In this case, the cost of the feedstock for cellulosic biofuels could be much lower than estimated above.

Discussion

As a high yielding crop that can be grown on semiarid lands with minimal inputs of water and nutrients, Agave is a promising feedstock for biofuels that can be grown without competing for land with food production. It is currently used primarily for producing tequila and mescal; but its future use for biofuel production is unlikely to be directly competitive with these high valued beverages. Instead the potential to expand production on unused but suitable land and to use the discarded biomass of the plant that is not used for beverage production creates an opportunity for adding value to the Agave plant and for producing economically viable biofuels.

The analysis in this paper suggests that the feedstock cost for biofuel from the piña alone, using a similar conversion process as for corn, could be US\$0.5–US\$.9 L^{-1} on average. While this is higher than the feedstock costs of corn ethanol and sugarcane ethanol currently there may be potential to reduce these costs with higher conversion efficiencies or by using sugar present in other parts of the plant. Costs of production could also be lower if Agave is grown on lower cost land not in demand for mescal or tequila. The costs of cellulosic biofuels using the biomass from the entire plant could be lower depending on the conversion efficiency of biomass to fuel and the costs of harvesting, collecting and transporting the biomass.

This analysis should be considered as being exploratory only. There are several gaps in the technical and economic information available that need to be filled before a rigorous assessment of the viability of *Agave*-based biofuels can be undertaken. On the technical side, these gaps include the lack of scientific information about the conversion efficiencies of using the piña and/or the biomass of the plant to produce biofuels. Also a more accurate determination of the usable biomass and sugar from the plant would enable detailed estimation of the feedstock costs of cellulosic biofuels from Agave. Information on the potential coproducts from producing biofuels using Agave, including electricity from the bagasse, and on the energy intensity and the greenhouse gas emissions intensity of the biofuel production process would allow assessment of the environmental sustainability of these biofuels.

The estimate of costs of production provided above is based on a labor intensive process with current low costs of labor in Mexico. Large-scale production of biofuels is likely to either significantly increase demand for labor or require some conversion to mechanized harvesting and field operations for Agave. These could raise the costs of production of biofuels. The feasibility of mechanization on the terrain on which Agave is typically grown needs to be assessed. Additionally, the costs of harvesting and utilizing the leaves and other parts of the plant are not known for *A. tequilana* and mescal feedstocks at this time and this could further increase the feedstock cost of biofuels. To the extent, that these costs of harvesting the other parts of the *A. tequilana* and mescal feedstocks are similar to the costs of harvesting the leaves of henequen, information on the latter could be used to develop estimates of the costs of biomass from *A. tequilana* and mescal feedstocks.

Conclusions

Agave is a promising biofuel crop given that it is not a major food or feed crop itself, and it does not require the highly productive lands necessary for biofuel crops such as corn. Given that only 10–30% of lands suitable for Agave production are currently in use in Mexico, there is seemingly a large capacity to expand production of Agave. However, there are still several barriers to the large-scale implementation of Agave. The conversion rate of corn grain–ethanol is still considerably higher than that from the sugars available in the Agave piña (using first-generation technology) which makes Agave an expensive feedstock. Thus, it would be imperative that large-scale Agave-to-ethanol production should capture and convert biomass available in the leaves and bagasse to enhance its ability to compete in the marketplace. The potential deleterious effects on soil fertility of removing leaves from the fields, as is currently practiced, will need to be assessed. In addition, Agave biofuel producers will very likely increase demand for labor or invest in mechanization technology to scale up their operations. This could result in increased employment opportunities and contribute to economic development. Planting and cultivation of Agave has already been mechanized to some extent for the production of *A. tequilana* supporting the tequila industry; however, these practices are not widespread. Mechanized harvesting practices are not widely available currently and will need to be developed. More research is therefore needed on the techno- and socio-economics of the feedstock production and conversion process to undertake a comprehensive assessment of the economic viability of *Agave* biofuels.

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