Energy and carbon footprints of ethanol production using banana and cooking banana discard: a case study from Costa Rica and Ecuador

Authors:

Sophie Graefe[a,]*, Dominique Dufour[a,b], Andrés Giraldo[a], Luis Armando Muñoz[a], Paola Mora[a], Hortensia Solís[c], Hernán Garcés[d], Alonso Gonzalez[a]

[a]International Center for Tropical Agriculture (CIAT), Km 17 Recta Cali-Palmira, Cali, Colombia
[b]Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), UMR Qualisud, 73 Rue Jean-François Breton, 34398 Montpellier, France
[c]Cooperativa de Caficultores de Dota (Coopedota), Santa María de Dota, Costa Rica
[d]Escuela Superior Politécnica del Litoral (ESPOL), Km 30.5 Via Perimetral, Guayaquil, Ecuador

*****Corresponding author. Tel.: +57 2 4450000 ext. 3308; Fax: +57 2 4450073.
E-mail address: s.graefe@cgiar.org

Abstract

Banana and cooking banana (*Musa spp.*) production systems accumulate a considerable quantity of discard due to high quality demands of markets. Ripe fruits have high sugar contents, which can be easily processed to ethanol. The present study aimed to quantitatively assess the production potential of ethanol from *Musa spp.* discard and to analyze the energy and carbon (C) footprints of this production system using a life cycle approach. The study compared three case studies differing in management practices, which were (I) a coffee producer's cooperative in Costa Rica using *Musa spp.* as shade trees, (II) organic banana producers from Ecuador, and (III) conventional banana producers from Ecuador. It was found that banana and cooking banana discard accumulated at a rate of 1.4-3.4 t ha^{-1}, of which around 118-266 l ethanol could be produced on a yearly basis. The case study from Costa Rica yielded a net-energy balance (NEB) of 19.3 MJ l^{-1} and avoided carbon emissions of 0.48 kg l^{-1}. It was closely followed by the organic banana producers from Ecuador with a NEB of 17.1 MJ l^{-1} and avoided carbon emissions of 0.44 kg l^{-1}. NEB and avoided carbon emissions for the conventional banana farms in Ecuador were much lower (7.2 MJ l^{-1} and 0.34 kg l^{-1}). Despite providing economic benefits to farmers through a biomass source that would have been otherwise lost, the study gave clear evidence that the ecological footprint of this ethanol

production system is significantly influenced by the resource use during the production life cycle.

Keywords: Carbon emissions, ethanol, life cycle analysis, *Musa spp.*, net-energy balance

Abbreviations

C	Carbon
CO_2	Carbon dioxide
DM	Dry matter
EtOH	Ethanol
FW	Fresh weight
K	Potassium
N	Nitrogen
NEB	Net-energy balance
P	Phosphorous

1. Introduction

Biofuels can contribute to support sustainable energy strategies and to reduce the dependency on fossil fuel imports, but it has to be considered that the energy efficiency and greenhouse gas reduction potential of biofuels strongly depends on how they are produced [1-3]. The cultivation and processing of crops that depend on high external inputs such as mineral fertilizers and pesticides can result in negative net-energy balances and high carbon footprints [4]. In addition to the environmental dimension also the social dimension of biofuels has to be taken into account, as the extended cultivation of biofuel crops can lead to competition with food crops and to deforestation of native forests, having impact on people that depend on natural resources to sustain their livelihoods [5], or simply have less access to land for cultivating the crops that offer food security. In this context the production of biofuels from waste biomass is regarded as a sustainable alternative without competing for alternative uses and areas [4]. However, not much information is available on environmental impacts of small-scale biofuel production in developing countries and case specific analyses are strongly needed to draw conclusions on environmental as well as socio-economic costs and benefits [6].

Bananas and cooking bananas (genome constitutions AAA, AAB, ABB) are derived from crosses between the wild species *Musa acuminata* (AA) and *Musa balbisiana* (BB) [7], and are considered to have the second highest energy yield per hectare after cassava [8]. They are either cultivated by smallholders in association with other food crops at low densities (i.e. as shade trees for perennials such as coffee or cacao) or in commercial plantations at high densities (in this case mainly banana). For Ecuador it is estimated that 10-12% of all economically active people obtain some benefit from banana production and 80% of total export production comes from growers that cultivate areas smaller than 30 ha [9]. Around 20-40% of the bananas that are produced do not meet export standards or even quality demands of local markets, and are usually deposited in open-air dumps [10-12]. Alternative uses for these discards have to be explored, and in this regard the processing to ethanol is seen to have a potential both from an environmental as well as economic point of view.

The aim of the present study was to analyze the feasibility to produce ethanol from *Musa spp.* discard in different production systems of Costa Rica and Ecuador. The study aimed to collect production data from the regions, and to apply a life cycle assessment as a methodological framework for assessing the environmental impact that is attributable to the life cycle of ethanol, with a main focus on net-energy balances and carbon emissions. The study further aimed to quantify the economic benefit that farmers could obtain from this activity.

2. Materials and Methods

The first case study was conducted within a coffee cooperative in Costa Rica, which was located at an altitude of 1500-1900 m asl and comprised an area of 1500 ha small-scale coffee plantations providing livelihoods to approximately 780 families. *Musa spp.* are commonly grown together with coffee plants. The cooperative already operates an ethanol processing plant for the residues that accumulate during the post-harvest processing of coffee, which are approximately 3 million tonnes coffee pulp per year. It is estimated that from this residues around 182 m^3 ethanol could be produced (Coopedota, unpublished data). As coffee bean harvest takes place only during three month of the year, there is a free capacity of the processing plant for the rest of the year, which could be used to produce ethanol from *Musa spp.* discard.

The second case study was conducted in Ecuador and covered two groups of banana producers. The first target group was composed of medium-size organic banana farms in the provinces of Guayas and Chimborazo at an average altitude of 440 m asl. The second target group covered conventional small-scale banana producers in the lowlands of the province of Guayas at an altitude of about 26 m asl. In the Ecuadorian case a processing plant is not yet available, but a plant with a processing capacity of 500 l day^{-1} is under construction.

For both case studies interviews were conducted with farmers in order to collect data about the availability of *Musa spp.* biomass, cultivation practices, economic returns from agricultural activities and gasoline demands of households. In Costa Rica interviews were conducted with 80 farmers and in Ecuador with 20 farmers. This baseline data as well as secondary data from literature (Table 1) was used to calculate energy and carbon footprints using a life cycle approach [6,13-15]. The life cycle analysis considered energy consumption and carbon emissions for all relevant stages of production, which were (I) agricultural production (use of fertilizers and pesticides), (II) transport of biomass from the field to the processing plant and (III) processing of the feedstock to ethanol.

Table 1

A theoretical approach was applied for estimating the conversion efficiency of *Musa spp.* biomass to ethanol. During the fermentation of glucose one glucose molecule is converted into two ethanol and two carbon dioxide molecules:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \qquad (1)$$

We estimated ethanol yields by taking the total fermentable sugar concentration (i.e. sucrose, fructose, glucose) of ripe banana and plantain varieties (Table 2), and converting them to ethanol through the ratios of atoms of each element, which was calculated as

$$EtOH = (TS * 0.51) / 0.79 \quad (2)$$

where EtOH is the ethanol yield of dry matter concentration ($l\ t^{-1}$); TS the total sugar concentration in dry matter of ripe varieties ($g\ g^{-1}$); 0.51 the share of the atomic weight that is converted to ethanol; and 0.79 the density of ethanol.

Table 2

The net-energy balance (NEB) of ethanol production was calculated as

$$NEB = EC_{ethanol} – EC_{fossil\ energy} \quad (3)$$

where $EC_{ethanol}$ is the energy content of ethanol (21.06 MJ l^{-1}, Table 1); and $EC_{fossil\ energy}$ the fossil energy that is consumed during cultivation, transport and processing of the ethanol feedstock (MJ l^{-1}).

Another indicator for energy efficiency is the energy output/input ratio, which refers to the output of ethanol energy per unit fossil energy used, and was calculated as

$$Output/input = EC_{ethanol} / EC_{fossil\ energy} \quad (4)$$

Avoided carbon emissions (which are defined as those C emissions that are avoided when biofuel is used instead of petroleum based gasoline) were calculated as

$$C_{avoided} = (C_{fossil\ fuel} – C_{ethanol}) * 0.65 \quad (5)$$

where $C_{avoided}$ are avoided carbon emissions (kg l^{-1}); $C_{fossil\ fuel}$ carbon emitted during production and combustion of fossil fuels (0.85 kg l^{-1}, Table 1); $C_{ethanol}$ carbon emitted during the life cycle of ethanol production (kg l^{-1}), including the agricultural production stage; and 0.65 the factor to convert $C_{avoided}$ to the energy content of ethanol, which is 65% of the energy content of gasoline. Carbon emitted during combustion of biofuels was not taken into account, as it was assumed that this carbon had been captured as CO_2 from the atmosphere by photosynthesis during plant growth.

3. Results

3.1 Production data

3.1.1 Costa Rica

The average farm size of the coffee producers belonging to the cooperative was 4.6 ha and was located at an average distance of 5.7 km to the processing plant. Coffee bean yield was 1.7 t ha^{-1} y^{-1} and generated a yearly gross income of about 1800 \$ ha^{-1}. Nitrogen, Phosphorous and Potassium were applied at rates of 180, 50, and 150 kg ha^{-1} y^{-1}. *Musa spp.* were commonly grown within the plantations to provide shade and organic matter for the coffee trees, and to improve the microclimate in the fields. The most widespread *Musa* species within the cooperative was Guineo, which is a starchy non-plantain cooking banana (AAAea) originating from the East African Highlands [27]. Additionally, about two thirds of the farmers cultivated several banana and cooking banana varieties, including plantain (AAA, AAB, ABB). Mean plant density of *Musa spp.* was 350 plants ha^{-1}, resulting in a yearly biomass of 5.4 t ha^{-1} (Table 3). The diverse range of *Musa spp.* plants were regarded as beneficial for coffee plants and did not receive extra inputs.

It was found that more than 40% of Guineo fruits were left to be rotten in the field, whereas around one third were used as animal feedstock. Only a small amount of Guineo was used for home consumption or sold on the market (Fig. 1). On the other hand more than 50% of bananas and cooking bananas (plantain) were used for home consumption; a considerable smaller percentage was sold on markets or used as animal feed. The accumulation of banana and plantain discard was less than 15% of the total harvest (Fig. 1). Accordingly, the waste biomass of Guineo, banana and cooking banana (plantain) that would be available for the processing to ethanol amounted to 1.4, 0.13 and 0.08 t ha^{-1} y^{-1}. This would be equivalent to a total pulp biomass (biomass that will be processed, without peel) of approximately 960 kg ha^{-1} y^{-1} or an ethanol yield of 131 l ha^{-1} y^{-1} (Table 3).

Fig. 1

Musa spp. varieties perform differently in terms of ethanol yield, which is mainly a result of compositional characteristics such as pulp to peel ratio, dry matter and sugar concentrations [24]. For the Costa Rican case study the highest ethanol yields per bunch would be obtained from bananas (several varieties, 3.0 liter per bunch) rather than cooking bananas (in this case Dominico and Guineo, both 1.8 liter per bunch), which is mainly due to higher bunch weights and sugar concentrations of bananas (Table 3).

Table 3

3.1.2 Ecuador

The first target group (organic banana farms) had an average size of 31.3 ha, of which around 20 ha were solely dedicated to banana production (varieties: Bocadillo, Tafetan). The remaining area was destined to other crops such as coffee, cacao, maize and pastures. The average plant density was 1112 plants ha^{-1} for the Bocadillo variety and 625 plants ha^{-1} for the Tafetan variety, yielding around 19.5 and 11.1 t ha^{-1} y^{-1}, respectively (Table 4). Mineral fertilizers were not applied and it was assumed that nutrient inputs to the farming system were generated on-farm, such as animal manure from cattle, goats, and sheep, cacao and banana leaves, banana peels and leguminous species as cover crops. However, organic farmers were forced to apply bio-fungicides.

The conventional small-scale banana farms of the second target group had an average size of 2.7 ha, of which 2.5 ha were destined for the cultivation of bananas (variety: Cavendish). Plant density was around 1216 plants ha^{-1}, resulting in a yield of 40.9 t ha^{-1} y^{-1} (Table 4). In this production system Nitrogen and Potassium were applied at rates of 300 and 450 kg ha^{-1} y^{-1}, and pesticides at a rate of 40 kg ha^{-1} y^{-1}, indicating a high us of external inputs.

As in the two Ecuadorian case studies a processing plant was not yet available, it was assumed that a future processing plant would be located at an average distance of 10 km from the fields; this was taken as the basis for calculating the energy demands for the transport of the feedstock from the field to the processing plant. Bananas of both production systems were destined for national and export markets, whereas the use for home consumption or as animal feed was insignificant. It was estimated that 8.3% of the total banana production was lost as discard, which corresponded to a pulp biomass of 0.84 t ha^{-1} y^{-1} for the organic farms and 2.1 t ha^{-1} y^{-1} for the conventional farms, or potential EtOH yield of 118 and 266 l ha^{-1} y^{-1}, respectively (Table 4). Both banana varieties of the organic farms had a much lower EtOH yield per bunch (Bocadillo: 2.1 liter per bunch, Tafetan: 2.1 liter per bunch) than the Cavendish variety of the conventional producers (3.1 liter per bunch), which was mainly attributable to the high bunch weight of the latter (Table 4).

Table 4

3.1.3 Yield potential of varieties

Fig. 2 summarizes potential ethanol yields for several banana and cooking banana varieties grown under similar conditions at different altitudes (i.e. <500 m asl and 1000-1500 m asl, representing the altitudinal range of the case studies in Costa Rica and Ecuador). Ethanol yields for banana varieties are approximately 1.6 times higher at altitudes <500 m asl than at altitudes 1000-1500 m asl, which is mainly due to shorter production cycles in warmer climates. Cooking banana varieties like Guineo, Guayabo and Dominico on the other hand are not cultivated at such low altitudes. At altitudes <500 m asl the highest EtOH yield on a hectare basis would be obtained for the dessert hybrid variety FHIA 1 (386 l ha^{-1} y^{-1}), followed by the banana varieties Gros Michel (290 l ha^{-1} y^{-1}) and Cavendish (250 l ha^{-1} y^{-1}). At altitudes between 1000-1500 m asl the highest EtOH yields would be obtained for Gros Michel (181 l ha^{-1} y^{-1}) and Bocadillo (196 l ha^{-1} y^{-1}). Other banana varieties (i.e. Cavendish, 156 l ha^{-1} y^{-1}) or cooking banana varieties (i.e. Dominico, 149 l ha^{-1} y^{-1} and Maqueño, 162 l ha^{-1} y^{-1}) showed also relatively high EtOH yields at the higher altitude. However, it should be considered that the cultivation of more traditional cooking bananas would be rather not practiced at such a high plant density that was chosen for this simulation.

Fig.2

3.2 Energy and carbon footprints

Potential energy inputs to the biofuel production chain originated from the manufacturing and application of fertilizer and pesticides, from transportation of the biomass from the field to the processing plant as well as from energy requirements of the processing plant. The conventional banana producers of Ecuador showed the by far highest energy and carbon footprint during the ethanol production life cycle, which corresponded to an energy consumption that was roughly 3.5 times higher than that of the organic banana producers (Fig. 3A). Regarding the organic banana producers no energy and carbon credits were related to fertilizers, as it was assumed that this resource originated within the farm boundary, such as from animal manure and plant residues. However, under the pesticides category some inputs were credited to fungicide applications. The lowest energy and carbon footprint was obtained for the Costa Rican case study, where energy and carbon credits were only related to the transportation of the biomass and the processing of the feedstock (Fig. 3B).

Fig. 3

The best net-energy balance (NEB) was obtained for the case study from Costa Rica (19.3 MJ l^{-1}), closely followed by the organic banana production system of Ecuador (17.1 MJ l^{-1}). Both systems operated with low external input, which was especially due for the Costa Rican case study, where Musaceas are planted as secondary crops in the coffee fields. The net-energy balance for the conventional banana farms in Ecuador was much lower (7.2 MJ l^{-1}), mainly due to the high energy credits of fertilizers and pesticides on which this system depended (Table 5). Avoided carbon emissions showed principally the same tendency, with the case study from Costa Rica yielding the highest avoided emissions (0.48 kg l^{-1}), followed by the organic and the conventional banana producers of Ecuador (0.44 and 0.34 kg l^{-1}, Table 5). Fertilizer manufacture had a lower carbon than energy footprint (Fig. 3.), which might be the reason that the conventional banana farms of Ecuador scored better in avoided carbon emissions than in net-energy balance.

Table 5

Fig. 4 shows the sensitivity of the net-energy balance to changes in the five key parameters that influence the energy footprint of the ethanol system. NEB reacted most sensitive to changes in the amount of mineral N fertilizer, but also to the application of pesticides. NEB was less sensitivity to changes in distance to the processing plant, energy requirements of processing plant and application of K fertilizer.

Fig. 4

3.3 Nutrients and co-products

A co-product from the processing of ethanol is stillage, which accumulates at a rate of 12 l per l ethanol processed [23]. The Nitrogen, Phosphorous and Potassium concentration of banana stillage is estimated to be 1.7, 0.2 and 2.8 g l^{-1} [10]. This co-product could be possibly recycled on-farm providing nutrients to the fields. In the present case study stillage could recover around 3.8 – 7.2 % of nutrients that are removed from the fields through banana cultivation (Table 6).

Table 6

3.4 Economic impact

Yearly gasoline consumption of the farm households varied between 1100 and 1700 l y^{-1}, corresponding to yearly gasoline expenditures of 1110 to 2360 \$ y^{-1} (actual gasoline prices are much lower in Costa Rica (0.97 \$ l^{-1}) than in Ecuador (1.40 \$ l^{-1}) (Table 7). Based on the production potential of the case study farms it could be estimated that in the case of Costa Rica 52% and in the case of the Ecuadorian small-scale farms 40% of the gasoline consumption of farm households could be replaced by ethanol from *Musa spp.* discard (assuming that vehicles can run on any combination of ethanol and petrol), which would be equivalent to saved gasoline expenditures of 582 and 931 \$ year^{-1}, respectively. The medium-sized organic banana farms of Ecuador would produce two times more ethanol than would be currently expended by the farm households.

The replacement of conventional gasoline with ethanol produced from *Musa spp.* discard could allow farm households to save carbon emissions in the range of 288, 1038 and 226 kg y^{-1} for the case studies from Costa Rica, Ecuador organic and Ecuador conventional, respectively. Avoided carbon emission for the Costa Rican case study would be even higher considering the ethanol production potential from coffee waste, which was not considered in this study.

Table 7

4. Discussion

Morris [28] distinguishes two types of land use change which may result from biofuel production, which is direct land use change through a conversion of non-crop land into energy crop land, and indirect land use change through a displacement of food and feed crops on existing crop land by energy crops. We assume that in the case of the present biofuel system, which focused on using banana and cooking banana discard as a feedstock for ethanol production, neither direct nor indirect land use changes occur, as it is a waste product which would have been otherwise lost. However, such a production system can only be regarded as sustainable when net-energy balances are clearly positive, and when avoided carbon emissions exists compared to petroleum based fuels. The more external inputs enter the production system, the larger is its ecological footprint. This was strongly reflected by the conventional banana producers in Ecuador, which were forced to apply high amounts of mineral fertilizers and pesticides, resulting in a NEB that was 2.4 times lower than the NEB of the organic banana producers. In this regard the life cycle approach proved to be a valuable screening tool for analyzing the resource use of such production systems. To define a sustainable bioenergy system, Zah et al. [29] suggest a threshold value for greenhouse gas reduction of at least 30% as compared to the fossil fuel reference, as well as no increasing impacts on other relevant environmental parameters.

In terms of energy output/input ratios the three case studies compared quite well to other ethanol systems. A literature review on output/input ratios of different production systems found a high variability even for similar crops (Fig. 5), which may be explained by a high variability of cultivation practices and external inputs used, but also by different assumptions made regarding system boundaries and conversion efficiencies. In some bioenergy systems, the feedstock's nutrient content can be recovered from the conversion facility in the form of ash or sludge and then converted into a form that can be applied to the field [30], which may positively influence energy and carbon footprints. In the case of bananas and cooking bananas further research is required on how co-products from ethanol production could be recycled on-farm.

Fig.5

Nitrogen fertilizer usually represents the single largest component of energy and CO_2 costs in land use systems [31], and may result in further disadvantages at the landscape level such as eutrophication and acidification 29]. Regarding the conventional banana farms of Ecuador nitrogen fertilizer accounted for 53 % of total energy consumption and 38 % of total carbon emissions during the ethanol lifecycle. It is well known that in conventional banana production systems major environmental impacts exist and ecologically sound management alternatives are strongly needed. Pests may develop resistances to chemicals, which creates a positive feedback to the need for higher quantities of external inputs and new chemicals to maintain production levels. It is estimated that for each tonne of bananas exported 3 t of waste is produced, of which only about 11% are organic wastes [11].

Another important indicator of resource use intensity of bioenergy systems is its water footprint, which is defined as the amount of water that is consumed to produce one unit of energy (m^3 GJ^{-1}), including the water that is required to grow the crops. It should be considered that biofuels have generally high water footprints, which may range from 1,400 to 20,000 l of water per l biofuel (equivalent to 66-950 m^3 GJ^{-1} energy produced). This is much larger than the water footprint of fossil energy (1.1 m^3 GJ^{-1}) [32]. Also *Musa spp.* have a high water footprint of around 875 m^3 t^{-1} [33], which is equivalent to 7.5 m^3 l^{-1} EtOH produced. One advantage of bananas and cooking bananas to other starchy crops such as cassava (*Manihot esculenta*) is the fact that the ripening process results in the hydrolysis of starch to sugar [25,26,34], which does not require enzymes for ethanol processing. Despite of some reductions in dry matter contents through respiration losses (Table 2), it is highly recommend to process *Musa spp.* biomass in a ripe stage. For dessert banana varieties the optimal sugar concentration would be obtained about eight days after ripening, and for cooking bananas at least twelve days after ripening [25]. Due to higher sugar contents banana varieties perform better in terms of ethanol yield than cooking bananas, and were comparable to ethanol yields of cassava. Sriroth et al. [35] reported a conversion ratio of fresh cassava roots to ethanol of 6:1. The best conversion ratio we estimated was 6.4:1 for the banana variety Bocadillo, which corresponded to an ethanol yield of 157 l t^{-1}. Other authors [10,36] reported banana feedstock conversion efficiencies of 100-120 l t^{-1}, which are comparable to the ethanol yields we obtained for the varieties Cavendish and Gros Michel.

The study revealed that considerable amounts of ethanol could be produced both from market oriented production systems with banana bunches that do not meet quality standards, as well as from low input agroforestry systems where *Musa spp.* are cultivated as secondary crops which are partly left to be rotten in the fields. In this context further attention should be drawn on determining how the produced ethanol could be used to optimize economic returns, i.e. by the producers themselves replacing gasoline consumption on-farm, or to be sold on a regional ethanol market. FAO [37] suggest that biofuels are best produced in a landscape mosaic where they are grown alongside food crops and other vegetation and provide valuable benefits such as ecosystem services, and where smallholders have the opportunity to use the biomass as an energy source for themselves. When environmental and food security concerns are taken into account, bioenergy options could be an important tool for improving the well being of rural people. We further recommend to not only focus on approaches that use single crops as feedstock, but rather to explore the possibility to also include other crops or crop discards that do not compete for alternative uses, such as cassava, which may be grown in the same land use mosaics. As biofuels may contribute to avoided carbon emissions, it should be further assessed how this approach could be integrated in PES schemes (payment for environmental services) under the clean development mechanism (CDM).

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Table 1. Data input for life cycle calculations.

Parameter	Unit	Quantity	Reference
Energy value banana	MJ t^{-1}	3852	[16]
Energy value cooking banana	MJ t^{-1}	5105	[16]
Fuel demand pickup truck (biomass transport)	l 100 km^{-1}	9.5	Own estimate
Loading capacity of pickup	t	1	Own estimate
Energy used for gasoline production	MJ l^{-1}	38.9	[14]
Energy used by processing plant	MJ l^{-1}	1.208	[17]
Energy used for N fertilizer production	MJ kg^{-1}	78.23	[18]
Energy used for P fertilizer production	MJ kg^{-1}	17.5	[18]
Energy used for K fertilizer production	MJ kg^{-1}	13.8	[18]
Energy used for pesticide production	MJ kg^{-1}	209	[19]
Energy value ethanol	MJ l^{-1}	21.06	[20]
C emissions from gasoline production	kg l^{-1}	0.85	[14]
C emissions from power generation	g MJ^{-1}	80	[13]
C emissions from N fertilizer production	g kg^{-1}	1255.3	[21]
C emissions from P fertilizer production	g kg^{-1}	61.9	[21]
C emissions from K fertilizer production	g kg^{-1}	76.2	[21]
C emissions from pesticide production	g kg^{-1}	6996	[19]
N depletion from coffee cultivation	kg t^{-1}	35	[22]
P depletion from coffee cultivation	kg t^{-1}	2.6	[22]
K depletion from coffee cultivation	kg t^{-1}	42	[22]
N depletion from banana cultivation	kg t^{-1}	2	[22]
P depletion from banana cultivation	kg t^{-1}	0.3	[22]
K depletion from banana cultivation	kg t^{-1}	5	[22]
Stillage accumulation from EtOH production	l l^{-1}	12	[23]
N concentration of stillage	g l^{-1}	1.71	[10]
P concentration of stillage	g l^{-1}	0.165	[10]
K concentration of stillage	g l^{-1}	2.81	[10]

Table 2. Compositional characteristics of major *Musa spp.* varieties from Costa Rica and Ecuador (green = before ripening, ripe = 8-12 days after ripening).

	Costa Rica			Ecuador organic		Ecuador conventional
	Guineo	Dominico	Banana varieties	Bocadillo	Tafetan	Cavendish [c]
Pulp (%) [a]	57.8	64.9	62.0	59.1	65.8	62.0
Dry matter (green) (%) [b]	24.1	42.8	29.4	34.6	26.9	26.6
Dry matter (ripe) (%) [b]	22.4	38.7	25.1	28.7	26.2	24.3
Starch (green) (mg g^{-1} dm) [a]	841	869	819	826	770	669
Sucrose (ripe) (mg g^{-1} dm) [b]	5.7	1.4	72.0	7.9	6.3	341.6
Fructose (ripe) (mg g^{-1} dm) [b]	362.8	261.8	365.6	406.1	310.5	177.0
Glucose (ripe) (mg g^{-1} dm) [b]	383.8	297.1	368.5	432.5	506.2	189.3
Total sugars (ripe) (g g^{-1} dm) [b]	0.75	0.56	0.81	0.85	0.82	0.71

[a] [24], [b] [25], [c] [26]

Table 3. Production data of the Costa Rica case study.

	Non-plantain cooking banana	Plantain	Banana	Total
Variety	Guineo	Dominico	Several varieties	-
# plants ha^{-1}	195	87	69	351
Bunch weight (kg)	16.4	12.9	23.2	-
Production cycle (month)	12	14	16	-
Biomass (t ha^{-1} y^{-1})	3.20	0.97	1.20	5.36
Discard (%)	43.7	13.1	8.8	-
Discard biomass (t ha^{-1} y^{-1})	1.40	0.13	0.11	1.64
Pulp biomass from discard (t ha^{-1} y^{-1})	0.81	0.08	0.07	0.96
Dry matter discard biomass (kg ha^{-1} y^{-1})	214.1	30.3	19.3	263.7
EtOH production potential (l t^{-1} dm)	487.5	363.1	522.3	-
EtOH production potential (l t^{-1} fw)	109.2	138.9	130.9	-
EtOH per bunch (l)	1.8	1.8	3.0	-
EtOH from discard (l ha^{-1} y^{-1})	104.4	12.8	13.4	130.5
EtOH from discard per farm (l y^{-1}) [a]	-	-	-	600
EtOH from discard for cooperative (l y^{-1}) [b]	-	-	-	195812

[a] Average farm size = 4.6 ha, [b] Total area of cooperative = 1500 ha

Table 4. Production data of the Ecuador case studies.

	Organic farms (Chimborazo-Guayas)		Conventional farms (Guayas)
Average farm size (ha)	31.3		2.7
Varieties	Bocadillo	Tafetan	Cavendish
Average area banana cultivation (ha)	13.3	6.7	2.5
# plants ha^{-1}	1112	625	1216
bunch weight (kg)	13.5	16.2	28
Production cycle (month)	9	11	10
Yield ($t\ ha^{-1}\ y^{-1}$)	19.5	11.1	40.9
Discard (%)	8.3	8.3	8.3
Discard biomass ($t\ ha^{-1}\ y^{-1}$)	1.6	0.9	3.4
Pulp biomass from discard ($t\ ha^{-1}\ y^{-1}$)	0.96	0.61	2.1
Dry matter discard biomass ($kg\ ha^{-1}\ y^{-1}$)	331.2	163.6	695.9
EtOH production potential ($l\ t^{-1}$ dm)	548.6	533.3	458.7
EtOH production potential ($l\ t^{-1}$ fw)	157.2	131.1	111.5
EtOH per bunch (l)	2.1	2.1	3.1
EtOH from discard ($l\ ha^{-1}\ y^{-1}$)	139.8	74.5	266.0
EtOH from discard per farm ($l\ y^{-1}$)	2358		665.0

Table 5. Net-energy balances (MJ l^{-1}) and avoided carbon emissions (kg l^{-1}) of ethanol production from *Musa spp.* discard in Costa Rica and Ecuador.

	Costa Rica	**Ecuador (organic)**	**Ecuador (conventional)**
Total energy consumed (MJ l^{-1})	1.75	4.0	13.86
Energy content ethanol (MJ l^{-1})	21.06	21.06	21.06
Net-nergy balance (MJ l^{-1})	**19.31**	**17.06**	**7.20**
Total C emissions (kg l^{-1})	0.11	0.18	0.33
C emissions to produce 1 L gasoline (kg l^{-1})	0.85	0.85	0.85
Avoided C emissions (kg l^{-1}) [a]	**0.48**	**0.44**	**0.34**

[a] considering lower energy content of ethanol from biomass feedstock (65% of gasoline)

Table 6. Nutrient removals from *Musa spp.* production systems and potential nutrient recovery from ethanol co-products.

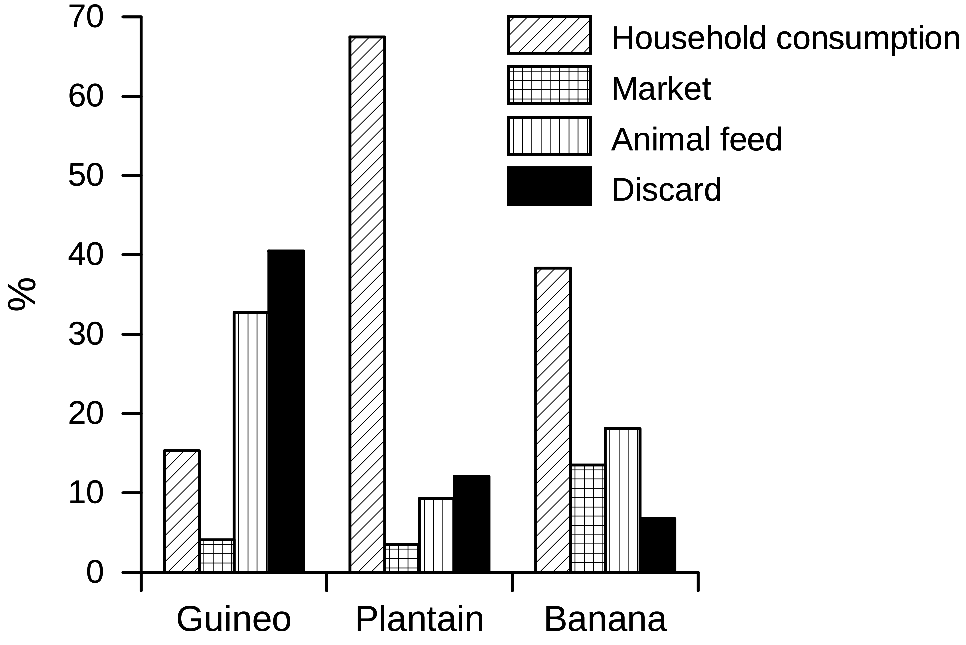
	Costa Rica	**Ecuador (organic)**	**Ecuador (conventional)**
N depletion (kg ha^{-1} y^{-1}) [a]	70.23	33.42	81.72
P depletion (kg ha^{-1} y^{-1}) [a]	6.01	5.01	12.26
K depletion (kg ha^{-1} y^{-1}) [a]	98.22	83.54	204.29
Stillage accumulation (l ha^{-1} y^{-1})	1566	1415	3192
N accumulation stillage (kg ha^{-1} y^{-1})	2.68	2.42	5.46
P accumulation stillage (kg ha^{-1} y^{-1})	0.26	0.23	0.53
K accumulation stillage (kg ha^{-1} y^{-1})	4.40	3.98	8.97
Potential N recovery from stillage (%)	3.81	7.24	6.68
Potential P recovery from stillage (%)	4.30	4.66	4.30
Potential K recovery from stillage (%)	4.48	4.76	4.39

[a] Including nutrient depletion from coffee cultivation for case study of Costa Rica.

Table 7. Economic key parameters of case study production systems.

	Costa Rica	Ecuador (organic)	Ecuador (conventional)
Gasoline consumption (l HH^{-1} y^{-1}) [a]	1144	1181	1684
Price gasoline ($ l^{-1}) [b]	0.97	1.4	1.4
Expenditure gasoline ($ HH^{-1} y^{-1}) [c]	1111	1653	2358
Ethanol production potential from *Musa* spp. discard (l $farm^{-1}$ y^{-1})	600	2358	665
Potential replacement of gasoline (%)	52	>100	40
Savings through own production ($ y^{-1})	582	1653	931
Gross income ($ ha^{-1} y^{-1})	(Coffee) 1797	(Banana) 3815	(Banana) 5873

[a] HH = household, [b] December 2009, [c] In Costa Rican case study 53% of vehicles run with diesel, 47% with gasoline; in Ecuadorian case study 100% of vehicles run with gasoline.



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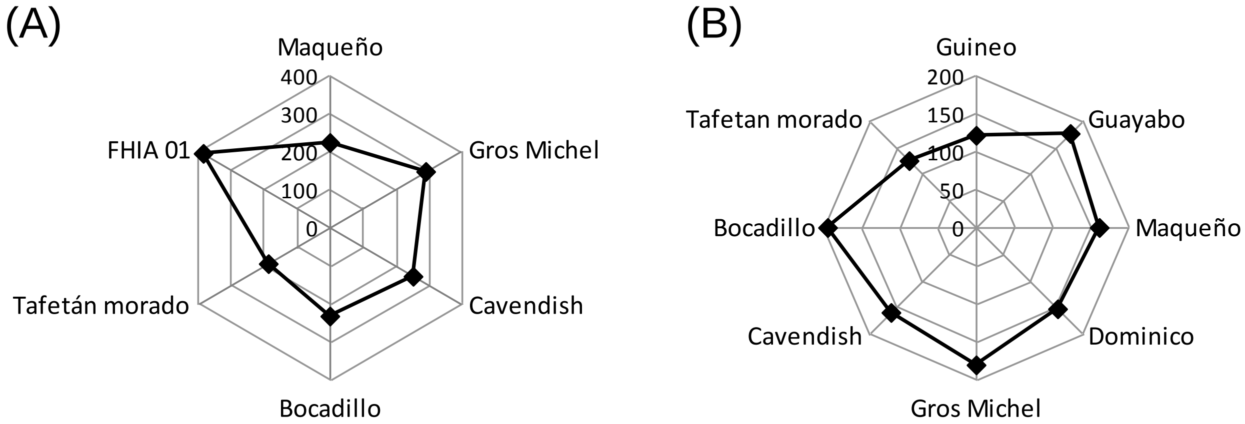

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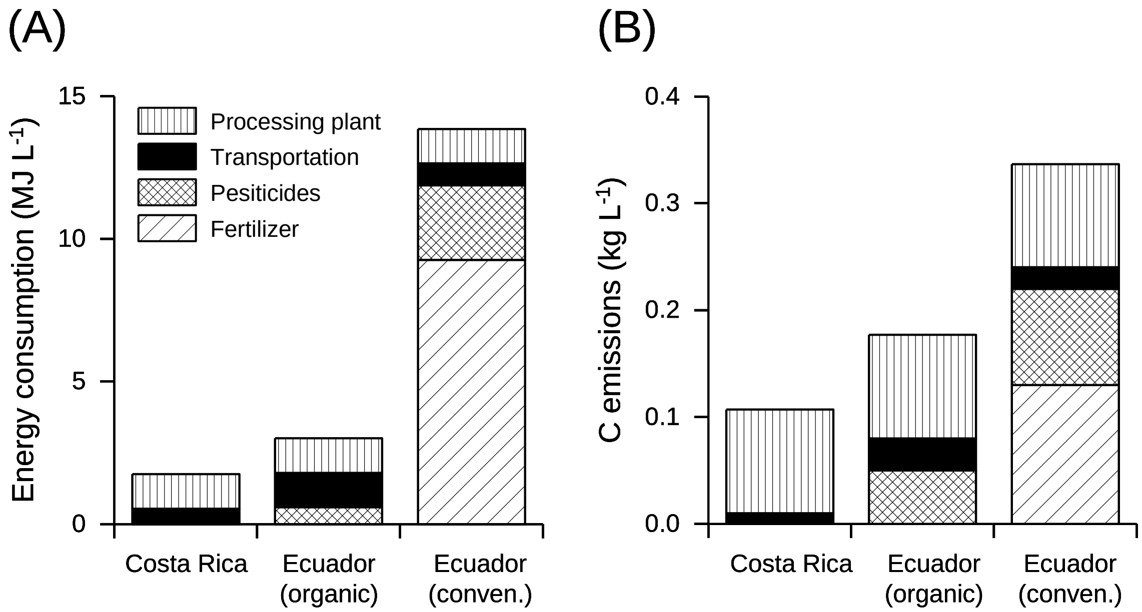

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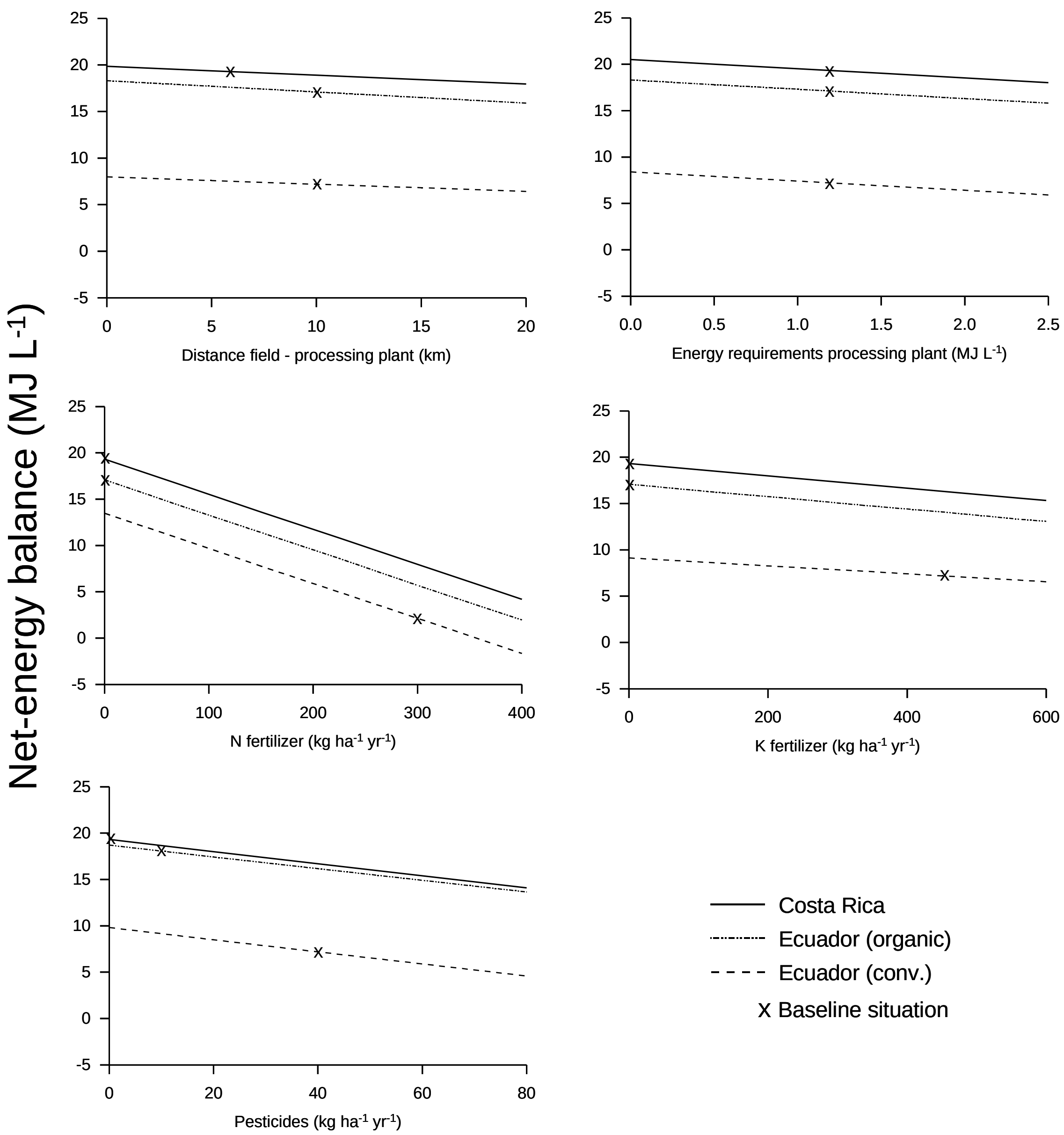

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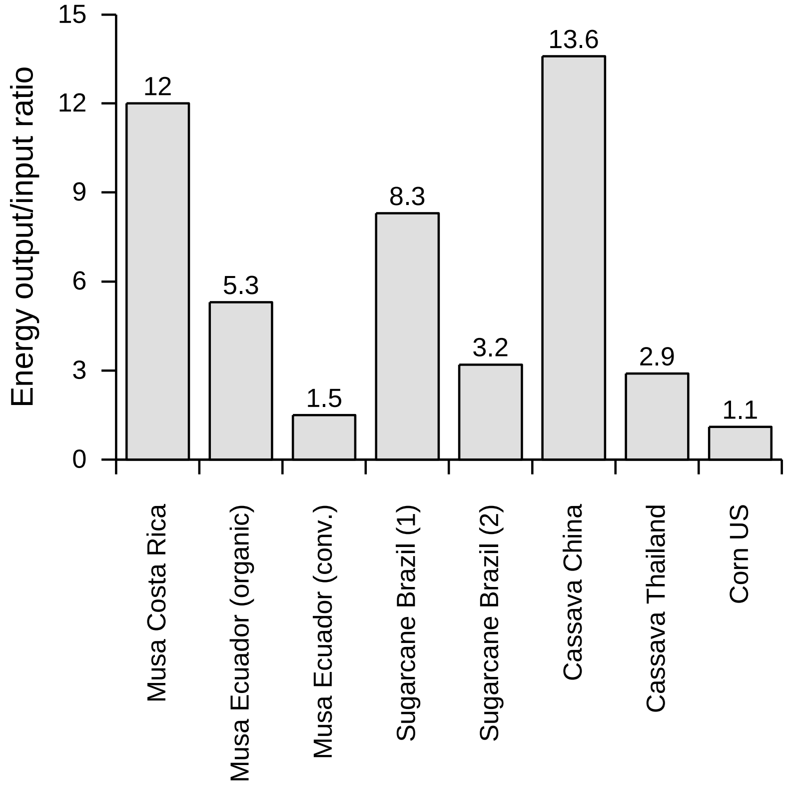

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