Assessing maize production systems in Mexico from an energy, exergy, and greenhouse-gas emissions perspective

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Abstract – Maize is the most important staple crop in Mexico and is cultivated under varied agro-climatic and socio-economic conditions. The aim of this study is to estimate energy use, cumulative exergy consumption (*CExC*), and greenhouse gas (GHG) emissions of different maize production systems as proxies to compare their resource use and environmental performance. Based on average values, per-hectare energy use, energy intensity (*EI*), energy output-input ratio (*ER*), and net energy (*NE*) are in the range of 2.3-40.2 GJ ha^{-1}, 1.8-8.5 MJ kg^{-1}, 1.7-12.0, and 16.3-73.1 GJ ha^{-1}, respectively. Per-hectare *CExC*, exergy intensity (*ExI*), exergy output-input ratio (*ExR*), and net exergy (*NEx*) are in the range of 2.5-52.1 GJ ha^{-1}, 1.9-10.7 MJ kg^{-1}, 1.6-14.1, and 19.6-86.8 GJ ha^{-1}, respectively. Per-hectare GHG emissions, GHG intensity (*GHGI*), and GHG per unit energy input ($GHGE_i$) are in the range of 152.9-3,475.8 kg CO_2e ha^{-1}, 116.5-601.9 kg CO_2e Mg^{-1}, and 63.1-117.2 kg CO_2e GJ^{-1}, respectively. Low-input rain-fed production systems perform better in *EI*, *ER*, *ExI*, *ExR*, *GHGI*, and $GHGE_i$ though, they also show the lowest *NE* and *NEx* due to poor yields. High-input surface irrigated production systems have the highest *NE* and *NEx* coupled with medium values of *EI*, *ExI*, and *GHGI* due to high productivity.

Keywords: rain-fed maize; irrigated maize; cumulative exergy consumption; global warming; sustainability.

Nomenclature

Notations	
app_rate	Farming input application rate
A-W	Autumn-winter growing season
CExC	Cumulative exergy consumption
D	Diesel energy
EF	Emission factor
EI	Energy intensity
En	Energy use
ER	Energy output-input ratio
ExI	Exergy intensity
ExR	Exergy output-input ratio
GHG	Greenhouse gas emissions
$GHGE_i$	Greenhouse gas emissions per unit energy input
GHGI	Greenhouse gas emission intensity
GWP	Global warming potential
n	Sample size
N	Number of times a field operation is performed
NE	Net energy
NEx	Net exergy
s_farmers	Per-cent share of farmers performing a given field operation or applying a given input
S-S	Spring-summer growing season
u	Absolute uncertainty
u%	Percentage (relative) uncertainty
$\bar{x}$	Mean value
Subscripts	
diesel	Diesel fuel
direct	Direct
fert	Synthetic fertilizer
field	Field operation
Field	Field operations
indirect	Indirect
input	Farming input
Inputs	Farming inputs
Irr	Irrigation pumping
Irr-diesel	Diesel use for irrigation pumping
Irr-elect	Electricity use for irrigation pumping
IrrEq	Irrigation equipment
mach	Farm machinery
Mach	Farm machinery (total)
total	Total
transp	Farming input transportation and distribution
Transp	Farming inputs transportation and distribution

1. Introduction

Maize (*Zea mays* L.) was originally domesticated in Mexico 7,000-10,000 years ago [1] and the country also hosts the world's richest diversity of maize varieties [2]. Historically, maize has been the most important staple crop in Mexico, comprising a large share of the national cropland and food crop production. Over the 2000-2014 period, average annual grain maize planted area in Mexico reached about 7.9 million ha with a total production of 21.2 million tons and an average yield of about 3.0 Mg ha^{-1} [3]. White maize is the most important maize variety in terms of planted area (94% of total maize area) and production (91%) as it is primarily used for direct human consumption [4]. Maize is considered a staple food crop for the majority of Mexican population [5] with an estimated consumption of about 267 g cap^{-1} day^{-1}, one of the highest in the world [6]. In Mexico, maize is cultivated under heterogeneous agro-climatic and socio-economic conditions, which results in a great diversity of maize production systems, ranging from traditional, small-scale subsistence production to large-scale, high-input commercial production [7,8]. Consequently, maize production systems use diverse management practices and hence, exhibit differing resources use patterns and environmental footprints.

Energy in modern crop production is used both directly (i.e. fuel for field operations, irrigation, etc.) and indirectly (i.e. manufacture of farming inputs, machinery, etc.) [9]. The amount and type of energy expended in crop production depends on numerous factors including crop type, management practices, climate, and soil properties. In the case of maize, several studies have assessed energy use in varied production systems and locations. For instance, energy requirements of 6.4 GJ ha^{-1} are reported for small-scale rain-fed maize in Thailand [10] and 10.7 GJ ha^{-1} for maize grown under arid conditions in India [11] while for high-input maize production in the U.S., estimates range from 30.0 GJ ha^{-1} [12] to 35.4 GJ ha^{-1} [13]. Published studies on energy use in maize production in Mexico, however, are scarce. Some authors have conducted detailed analyses of energy use in maize grown in rural communities in the west of the country [14,15] though, they only quantify direct energy inputs per unit land area. Other studies compare energy use in contrasting maize production systems but are limited to specific locations [16].

In addition to energy, crop production also requires material inputs, which should also be taken into consideration for a comprehensive resource accounting. Moreover, as resources differ in their quality or usefulness for a given purpose, a merely quantitative approach based on the mass and energy conservation laws may not provide a proper indication of process sustainability [17]. Accounting for both quantity and quality of energy and material flows on a common unit basis can be done through the concept of exergy [18]. Exergy is a measure of the amount of useful work that can be obtained from a system as it comes into thermodynamic equilibrium with the natural environment [19]. The concept of exergy relies on the second law of thermodynamics, which states that every real transformation process leads to the production of entropy and hence, a loss in the quality of the resources involved [20]. As different resources can be quantified on the exergy scale, the exergy method enables a more thorough resource accounting, suitable for evaluating the sustainability of different processes and production systems [20]. The exergy method has been used to measure the efficiency and sustainability of the agriculture sector as a whole [18] and the production of different agricultural products [21,22]. Maize production has also been examined from the exergy perspective as part of studies dealing with the sustainability of bio-ethanol production in the U.S. [23], Canada [24], and China [25]. These studies, however, only examine high-input, large-scale production systems. In the case of Mexico, existing exergy-based analyses of maize farming are limited to low- and medium-input production systems in a rural community in Michoacán State [14].

Agricultural activities are also an important source of greenhouse gas (GHG) emissions. In Mexico, agriculture contributes approximately 12% of total national GHG emissions [26]. Emissions from crop production also vary depending on numerous factors and hence, site- and crop-specific studies are necessary. Various studies have quantified GHG emissions from maize production in diverse locations around the world such as Thailand (160.0 kg CO_2e Mg^{-1}) [10], Canada (243.0 – 353.0 kg CO_2e Mg^{-1}) [27] and the U.S. (254.0 – 825.0 kg CO_2e Mg^{-1}) [28]. Nevertheless, few published studies exist about the GHG emissions from maize production in Mexico with some of them accounting only for CO_2 emissions [16] and others being restricted to specific locations and production systems [29,30].

Thus, efforts are needed to conduct additional studies of the flow of resources and environmental footprints of maize farming in Mexico taking into consideration the diversity of production systems in the country. This kind of studies may help identify possible interventions to enhance the long-term sustainability of maize production. Accordingly, the aim of this work is to estimate energy use, exergy consumption, and GHG emissions of different maize production systems in Mexico and derive a set of indicators to compare the resource use efficiency and environmental performance of the production systems.

2. Methods and sources of information

2.1 Maize production systems

Maize production systems were derived from the typology of cropping systems developed by the Mexican Agricultural Ministry [31]. This typology is based on (i) source of water (rain-fed, R;

surface irrigation, S; pressurized irrigation, P), (ii) type of seed (landrace seed, L; hybrid seed, H), and (iii) synthetic fertilizer treatment (without fertilizers, WO; with fertilizers, W) (Table 1).

2.2 Farming inputs and field operations

Farming inputs and field operations were obtained from grain maize production costs provided by the Mexican Agricultural Ministry [31]. Production costs are given on a per-hectare basis and detail the field operations performed, source of power used (i.e. manual, draft animals, or mechanical power), number of passes and time spent in each operation, applied farming inputs, grain yield, and share of farmers performing each operation and applying each input. Production costs are reported by maize system, Mexican state, and growing season (i.e. spring-summer, S-S, and autumn-winter, A-W). Post-harvest operations were omitted because they are reported only for a few production systems and locations. Data for Distrito Federal State were also excluded from the analysis because this Mexican state has negligible agricultural production.

Production costs data for rain-fed maize production systems were available mainly for the S-S season with limited data for the A-W season. Given that most rain-fed maize area is farmed during the S-S season (as it will be shown later), data for the A-W season were excluded. Production costs for RLWO, RHWO, RLW, and RHW production systems for the S-S season were available for six, three, eight, and 14 Mexican states, respectively (Table A1, Supplemental Material). Minimum, maximum, and average farming input rates of the rain-fed production systems are listed in Table A2. Regarding irrigated production systems, production costs for SLWO production system were available only for two Mexican states for the S-S season while data for SHWO production system existed only for one state for the S-S season and one for the A-W season. Given these data limitations, both SLWO and SHWO production systems were excluded. Note that, as it will be explained later, SLWO and SHWO production systems together comprise a minor share of total maize area and hence, calculations will not be greatly affected. Data for SLW production system were available for three states for the S-S season and one for the A-W season while data for SHW production system existed for eight and seven states, respectively. Data for pressurized irrigated production systems were available only for PLW and PHW production systems. The former was excluded because of limited data (i.e. only two states for the S-S season) and small associated planted area. In the case of PHW production system, data were available for six states for the S-S season and three states for the A-W season. Irrigation-related inputs (i.e. electricity, diesel, and human labor) were taken from [32]. Minimum, maximum, and average farming input rates of the irrigated production systems are given in Table A3. Note that [31] does not specify the fertilizer application method used and hence, it was assumed that manual application was done by hand broadcasting and mechanical application by surface broadcasting (for solid fertilizers) and soil injection (for NH_3). Although data from [31] refer to the 2005-2007 period, maize production systems have not changed radically in the last 10 years so data were taken as representative of the current practice.

2.3 System boundaries

System boundaries comprised the main direct and indirect energy and exergetic inputs and GHG emission (i.e. CO_2, N_2O, and CH_4) sources (Figure 1). Indirect energy and exergetic inputs included the production of seed, fertilizers, pesticides, farm machinery and irrigation equipment as well as the fossil fuels consumed for transportation and distribution of seed, fertilizers, and pesticides. Direct energy and exergetic inputs comprised diesel and electricity for field work and irrigation pumping; human and animal labor was accounted only for direct energy inputs while it was omitted from the exergy consumption analysis to avoid double-counting problems [33]. Energy and exergetic inputs related to solar radiation and water were not considered in both analyses. Indirect GHG emission sources included production of seed, fertilizers, pesticides, farm machinery and irrigation equipment, as well as fossil fuel consumption in input transportation and electricity generation. Direct GHG emission sources encompassed fertilizer application and diesel consumption for mechanical field operations. The former accounted for direct N_2O emissions from N-fertilizer application and CO_2 emissions from urea application. Indirect N_2O emission from N volatilization and leaching were not quantified. The output product was grain maize and so crop residues were unaccounted for.

2.4 Calculation of energy use

2.4.1 Indirect energy use

Per-hectare energy use in the production of seed, synthetic fertilizers, and pesticides was calculated as below:

$$En_{Inputs} = \sum_i \left(En_{input,i} \times app\_rate_i \times s\_farmers_i \right) \quad (1)$$

With En_{input} in MJ kg^{-1} or MJ L^{-1} and *app_rate* in kg ha^{-1} or L ha^{-1}. Values of En_{input} were taken from the literature (Table A4). Similarly, per-hectare energy use related to the manufacture of farm machinery involved in the field operations performed, was obtained as follows:

$$En_{Mach} = \sum_i \left(En_{mach,i} \times N_i \times s\_farmers_i \right) \quad (2)$$

Where En_{mach} is in MJ ha^{-1} and was derived from the relevant literature (Table A5).

Energy embodied in both farm hand tools and implements used in animal-driven field operations was omitted. Per-hectare En_{IrrEq}, in MJ ha^{-1}, was accounted only for the PHW production system using data from [32].

Energy requirements for international transportation of imported inputs and domestic transportation of both imported and nationally produced inputs were estimated using data on imports, exports, and domestic production of fertilizers, pesticides, and hybrid seed from [34–39] for the 2004-2008 period. Countries of origin of imports were consulted in [39], exit points in [40–42], and entry points in Mexico in [42]. Based on this information, average hauling distances and transportation modal shares were obtained for each exporting country and every farming input. Internal transportation of imports in the countries of origin was ignored except for imports from the U.S due to its spatial location relative to Mexico. For imports from the U.S., average hauling distance to the Mexican border by transportation mode was approximated from data provided in [43]. Energy intensities of maritime, rail, truck, and air transportation were set at 0.04, 0.20, 0.78 [44], and 20 MJ ton^{-1} km^{-1} [45], respectively. Relative contribution of each country to total imported volume of every farming input was used to compute weighted average transportation energy use per ton of input (Table A6). For domestic transportation in Mexico, modal share was assumed to be 80% truck, 11% rail, and 9% barge [46] with average hauling distances from [40,46,47] and energy intensities of 0.78, 0.32, and 0.31 MJ ton^{-1} km^{-1} [44,47], respectively. Distribution was assumed to rely entirely on truck transportation with an energy intensity of 1.12 MJ ton^{-1} km^{-1} and a hauling distance of 50 km [44]. Energy equivalents of transportation fuels included upstream energy use [44]. Embodied energy in vehicles and transportation infrastructure was not quantified. Per-hectare energy use for input transportation and distribution was calculated as:

$$En_{Transp} = \sum_i \left(En_{transp,i} \times app\_rate_i \times s\_farmers_i \right) \quad (3)$$

With En_{transp} in MJ kg^{-1} or MJ L^{-1} of transported input.

2.4.2 Direct energy use

Human and animal labor, diesel, and electricity requirements for field operations and irrigation pumping were obtained from the literature. Reported values for maize production in Mexico [14,15,48,49] were preferred. For operations with no maize-specific data available, standard values were used. Per-hectare energy use in field operations was computed using the following expression:

$$En_{Field} = \sum_i \left(En_{field,i} \times N_i \times s\_farmers_i \right) \tag{4}$$

Where En_{field} is in MJ ha^{-1}. For mechanical field operations, En_{field} was computed from associated diesel use in L ha^{-1} (Table A5) and diesel energy equivalent in MJ L^{-1}. For manual operations, En_{field} was obtained using the estimated human labor requirements, in MJ h^{-1} of work, as reported in the literature (Table A7) and the time spent in each operation, in h ha^{-1}, according to [31]. For animal-powered field operations, En_{field} compiled from the literature was already expressed in MJ ha^{-1} (Table A8). Human labor related to both operating machinery and directing draft animals was ignored. For both SLW and SHW production systems, En_{Irr} (in MJ ha^{-1}) comprised the electricity and diesel use for groundwater pumping and the human labor for irrigation application. In the case of PHW production system, En_{Irr} also included the electricity and diesel for operating the pressurized irrigation systems based on [32]. Energy equivalents of diesel and electricity (Table A4) accounted for upstream energy use. Total energy use per cultivated hectare was obtained as:

$$En_{total} = En_{indirect} + En_{direct} \tag{5}$$

Where:

$$En_{indirect} = En_{Inputs} + En_{Mach} + En_{IrrEq} + En_{Transp} \tag{6}$$

$$En_{direct} = En_{Field} + En_{Irr} \tag{7}$$

In addition, the following indicators were computed: *EI* (i.e. per-hectare total energy use divided by grain yield), *ER* (i.e. ratio of grain energy output to per-hectare total energy use), and *NE* (i.e. grain energy output minus per-hectare total energy use). Grain energy output was calculated assuming 18.3 MJ kg^{-1} grain (d.m.) [50] and grain moisture content of 25% [13].

2.5 Calculation of exergy consumption

Exergy consumption was computed as the *CExC*, which is defined as the exergy of all material and energetic inputs consumed along the production chain of a given product per unit of output product [33]:

$$CExC = \frac{\sum Ex}{m} \tag{8}$$

For calculation purposes, the exergy of energy carriers is usually derived from exergy-to-heating value ratios while in the case of raw materials it equals their chemical exergy [20].

2.5.1 Indirect exergy consumption

The *CExC* associated with the production of seed, synthetic fertilizers, pesticides, farm machinery and irrigation equipment as well as that of the fuels consumed for input transportation was regarded as indirect *CExC*. Values for farming inputs were derived from the literature (Table A4). Note that for various farming inputs, the *CExC* had to be estimated based on the inventory of the main material and energy inputs of production processes and their associated *CExC* from the literature. Corresponding per-hectare *CExC* was calculated using the following expressions:

$$CExC_{Inputs} = \sum_i \left(CExC_{input,i} \times app\_rate_i \times s\_farmers_i \right) \tag{9}$$

$$CExC_{Mach} = \sum_i \left(CExC_{mach,i} \times N_i \times s\_farmers_i \right) \tag{10}$$

$$CExC_{Transp} = \sum_i \left(CExC_{transp,i} \times app\_rate_i \times s\_farmers_i \right) \tag{11}$$

Note that for farm machinery, calculations relied on the *CExC* of steel (118 MJ kg^{-1}) [23] and the mass of each piece of machinery obtained from the previously computed per-hectare indirect energy use in machinery and the machinery specific energy (108 MJ kg^{-1}) [13]. The amount of fossil fuels consumed and their associated *CExC* were both employed to compute *CExC* in input transportation and distribution. With regard to irrigation equipment, material inputs for its production from [51] and corresponding *CExC* values from [23,33,52] were used to estimate $CExC_{IrrEq}$, in MJ ha^{-1}.

2.5.2 Direct exergy consumption

The $CExC_{field}$ was estimated from the corresponding per-hectare diesel use and the *CExC* of diesel and it was then used to calculate total *CExC* associated with mechanical field operations as follows:

$$CExC_{Field} = \sum_i \left(CExC_{field,i} \times N_i \times s\_farmers_i \right) \tag{12}$$

Diesel and electricity inputs for irrigation pumping and the *CExC* of diesel and electricity (Table A4) were used to estimate $CExC_{Irr}$, in MJ ha^{-1}. Next, total *CExC* per cultivated hectare was calculated:

$$CExC_{total} = CExC_{indirect} + CExC_{direct} \quad (13)$$

Where:

$$CExC_{indirect} = CExC_{Inputs} + CExC_{Mach} + CExC_{IrrEq} + CExC_{Transp} \quad (14)$$

$$CExC_{direct} = CExC_{Field} + CExC_{Irr} \quad (15)$$

In accordance with energy-based indicators, the following indicators were computed: *ExI* (i.e. per-hectare *CExC* divided by grain yield), *ExR* (i.e. ratio of grain exergy output to per-hectare *CExC*), and *NEx* (i.e. grain exergy output minus per-hectare *CExC*). Grain exergy output was calculated assuming a specific exergy content of 21.7 MJ kg^{-1} grain (d.m.) [50] and grain moisture of 25% [13].

2.6 GHG emissions

2.6.1 Indirect GHG emissions

Per-hectare GHG emissions from the production of seed, synthetic fertilizers, and pesticides and those from the manufacture of farm machinery were calculated as below:

$$GHG_{Input} = \sum_j \left[\sum_i \left(EF_{input,i,j} \times app\_rate_i \times s\_farmers_i\right)\right] \times GWP_j \quad (16)$$

$$GHG_{Mach} = \sum_j \left[\sum_i \left(EF_{mach,i,j} \times N_i \times s\_farmers_i\right)\right] \times GWP_j \quad (17)$$

Where EF_{input} is in kg GHG kg^{-1} or kg GHG L^{-1} and EF_{mach} in kg GHG ha^{-1} (Tables A5 and A9), and *GWP* is the global warming potential of the *j* GHG that was used to convert to CO_2 equivalent emissions (i.e. 1 for CO_2, 298 for N_2O, 25 for CH_4) [53]. The value of GHG_{IrrEq}, in kg GHG ha^{-1}, was taken from [32]. The amount of fossil fuels consumed for input transportation and distribution and the corresponding emission factors from [54,55] were both employed to estimate EF_{transp}, in kg GHG kg^{-1} or kg-GHG L^{-1} of input (Table A10), which was then used to calculate per-hectare GHG_{Transp}:

$$GHG_{Transp} = \sum_j \left[\sum_i \left(EF_{transp,i,j} \times app\_rate_i \times s\_farmers_i\right)\right] \times GWP_j \quad (18)$$

The average electricity generation efficiency and fossil-fuel mix for 2004-2008 period derived from [56] were used to estimate $GHG_{Irr\text{-}elect}$. Note that $GHG_{Irr\text{-}elect}$ included for emissions from upstream processing of fossil-fuels consumed based on [44].

2.6.2 Direct GHG emissions

Per-hectare GHG emissions from diesel consumption in field work were computed as follows:

$$GHG_{Field} = \sum_j \left[\sum_i \left(D_i \times EF_{diesel,j} \times N_i \times s\_farmers_i \right) \right] \times GWP_j \qquad (19)$$

With D in MJ ha^{-1} and EF_{diesel} in kg GHG MJ^{-1} of diesel energy. Note that EF_{diesel} accounted for GHG emissions from upstream diesel processing based on [44]. No GHG emissions were quantified for manual and animal-powered field operations. The amount of $GHG_{Irr\text{-}diesel}$, in kg GHG ha^{-1}, were retrieved from [32]. Emissions from synthetic fertilizer application included direct N_2O emissions from N-fertilizer and CO_2 emissions from urea computed using the following equation:

$$GHG_{Fert} = \sum_j \left[\sum_i \left(EF_{fert,i,j} \times f_j \times app\_rate_i \times s\_farmers_i \right) \right] \times GWP_j \qquad (20)$$

Where EF_{fert} amounts to 0.01 kg N_2O-N kg N^{-1} applied and 0.20 kg CO_2-C kg urea^{-1} applied [55] and f is the factor to convert N_2O-N into N_2O (44/28) and CO_2-C into CO_2 (44/12). Finally, per-hectare total GHG emissions were calculated as below:

$$GHG_{total} = GHG_{indirect} + GHG_{direct} \qquad (21)$$

Where:

$$GHG_{indirect} = GHG_{Inputs} + GHG_{Mach} + GHG_{IrrEq} + GHG_{Transp} + GHG_{Irr-elect} \qquad (22)$$

$$GHG_{direct} = GHG_{Field} + GHG_{Irr-diesel} + GHG_{Fert} \qquad (23)$$

In addition, the next indicators were calculated: *GHGI* (i.e. per-hectare total GHG emissions divided by grain yield), and $GHGE_i$ (i.e. ratio of per-hectare total emissions to per-hectare total energy use).

2.7 Uncertainty analysis

In accord with [57], the uncertainty in the mean values of compiled data was computed as the standard error of the mean:

$$u_x = \sqrt{\frac{\sum_i (x_i - \bar{x})^2}{n(n-1)}} \tag{24}$$

Where $\bar{x}$ is the mean of the n values of the variable x. The uncertainty was obtained for each of the mean values calculated for every energy and exergetic input and GHG emission source considered. To estimate the uncertainty in the set of indicators, the general formula for error propagation was employed [57]:

$$u_q = \sqrt{\left(\frac{\partial q}{\partial x} u_x\right)^2 + \cdots + \left(\frac{\partial q}{\partial z} u_z\right)^2} \tag{25}$$

where q is a function of the variables x, …, z. Note that as the indicators computed in the present study only involved sums/differences and products/quotients of the energy, *CExC*, and GHG emission variables, Eq. (25) reduces to the following expressions [57,58]:

$$u_q = \sqrt{u_x^2 + \cdots + u_z^2} \tag{26}$$

to compute the absolute uncertainty in sums/differences, and

$$u\%_q = \sqrt{u\%_x^2 + \cdots + u\%_z^2} \tag{27}$$

to compute the percentage uncertainty in products/quotients, with

$$u\%_q = \frac{u_q}{q} \times 100 \tag{28}$$

2.8 Country-scale estimates

Calculated average per-hectare energy use, *CExC*, and GHG emissions for each maize production system were scaled up to country-level using the total planted area under each production system as derived from the Agriculture and Forestry Census 2007 microdata (latest available) [59]. Details on selected microdata variables, calculation method, and assumptions made are given in [32]. It is worth mentioning here that due to restrictions of census microdata, the estimated national maize planted area comprises only crop farms that planted exclusively grain maize (i.e. maize monocrop planted area) [32].

3. Results

3.1 Energy use

Range and average of calculated per-hectare total energy use, relative shares of direct and indirect energy inputs, *EI*, *NE*, and *ER* are listed in Table 2. Estimates by Mexican state are given in Table A11, the relative contribution of the different inputs is shown in Figure A1, and the standard deviation of estimates is summarized in Table A12. Diesel for field operations was the single largest energy input in both RLWO and RHWO production systems, representing about 55% and 47%, respectively, of average per-hectare total energy use (Figure 2). Most of the remainder was attributed to farm machinery (13% and 12%, respectively), pesticides (12% and 14%), seed (11% and 22%), and human and animal labor (7% and 5%). As a result, direct inputs made up the largest proportion of average per-hectare total energy use in both RLWO and RHWO production systems. In the case of RLW and RHW production systems, fertilizers dominated the energy budget with around 65% and 63%, respectively, of average per-hectare total energy use, followed by diesel for field operations (13% and 14%), pesticides (8% and 6%), and seed (3% and 9%). Thus, indirect energy inputs took the largest proportion of average per-hectare total energy use in both RLW and RHW production systems.

With regard to irrigated production systems, average per-hectare total energy use was calculated using the national weighted average (by planted area) of irrigation energy inputs instead of state-level data. The reason for this was that state-level data may not be fully representative given that (i) irrigation-related inputs vary greatly across states due mainly to heterogeneous climatic conditions, and (ii) irrigated maize area concentrates in a few Mexican states [32]. Thus, the use national weighted averages of irrigation energy inputs was assumed to increase the representativeness of estimates. National weighted average of irrigation energy inputs for the irrigated maize systems investigated was retrieved from [32]. Therefore, in SLW production system, most energy use was related to fertilizers, with 42% of average per-hectare total energy use for the S-S season and 40% of that for the A-W season, and electricity and diesel for irrigation, with 32% and 42%, respectively, distantly followed by pesticides (10% and 6%) and diesel for field work (8% and 7%). In SHW production system, the major contributors to average per-hectare total energy use were fertilizers, with 57% of that for the S-S season and 65% of that for the A-W season, electricity and diesel for irrigation, with 16% and 6%, respectively, and diesel for field operations, with 12% and

14%. Consequently, indirect energy inputs dominated the energy budgets of both SLW and SHW production systems. In PHW production system, electricity and diesel for irrigation accounted for the largest share of average per-hectare total energy use, with around 53% and 75% of that for S-S and A-W seasons, respectively, followed by fertilizers (30% and 8%) and diesel for field operations (7% and 6%). Thus, direct energy inputs comprised the major proportion of average per-hectare total energy use for both growing seasons.

3.2 Cumulative exergy consumption

Range and average of per-hectare *CExC*, relative shares of direct and indirect exergetic inputs, *ExI*, *NEx*, and *ExR* are given in Table 3. Estimates by Mexican state are listed in Table A13, the relative contribution of the different inputs is illustrated in Figure A2, and the standard deviation of computed values is shown in Table A14. In RLWO and RHWO production systems, diesel for field work was the major single contributor with about 54% and 43%, respectively, of average per-hectare *CExC*, followed by pesticides (19% and 21%), farm machinery (14% and 12%), and seed (13% and 23%) (Figure 3). Overall, direct exergetic inputs comprised the largest proportion of average per-hectare *CExC* of RLWO production system while indirect exergetic inputs took the largest share of that of RHWO production system. In RLW and RHW production systems, fertilizers held the greatest proportion of average per-hectare *CExC*, representing about 72% and 69%, respectively, followed by diesel for field operations (10% and 11%), pesticides (9% and 7%), seed (3% and 8%), and farm machinery (2% and 3%). Thus, indirect exergetic inputs were the dominant contributor to average per-hectare *CExC* of both RLW and RHW production systems.

As in the energy analysis, average per-hectare *CExC* of irrigated production systems was calculated using the national weighted average of electricity and diesel inputs for irrigation pumping. In SLW production system, fertilizers made up the greatest share of average per-hectare *CExC*, accounting for about 48% of that for the S-S season and 47% of that for the A-W season, followed by electricity and diesel for irrigation (32% and 40%, respectively), pesticides (8% and 4%), and diesel for field work (7% and 5%). Fertilizers were the major contributor to average per-hectare *CExC* of SHW production system too, representing about 58% of that for the S-S season and 70% of that for the A-W season, followed by electricity and diesel for irrigation (17% and 6%, respectively), and diesel for field work (10% and 12%). Collectively, indirect exergetic inputs held the greatest fraction of average per-hectare *CExC* estimated for SLW and SHW production systems in both growing seasons. In PHW production system, electricity and diesel for irrigation together comprised the major share of average per-hectare *CExC*, with about 51% of that calculated for the S-S season and 74% of that for the A-W season, followed by fertilizers (32% and 9%, respectively), farm machinery and irrigation equipment (5% and 6%), and diesel for field operations (5% and 4%). Therefore, direct exergetic inputs together took the largest proportion of average per-hectare *CExC* calculated for PHW production system in both growing seasons.

3.3 GHG emissions

Range and average of computed per-hectare total GHG emissions, relative shares of direct and indirect emission sources, *GHGI*, and $GHGE_i$ are listed in Table 4. Estimates by Mexican state are summarized in Table A15, the relative contribution of the different emission sources is depicted in Figure A3, and the standard deviation of estimates is given in Table A16. Diesel consumption for field work was the main single source of emissions in both RLWO and RHWO production systems, representing about 68% and 49%, respectively, of average per-hectare total GHG emissions, followed by farm machinery (19% and 14%), pesticides (13% and 12%), and hybrid seed (24%) (Figure 4). Thus, direct emission sources were responsible for the majority of average per-hectare total emissions from RLWO production system while indirect emissions sources contributed the most to average per-hectare total emissions from RHWO production system. In both RLWO and RHWO production systems, CO_2 accounted for about 80-90% of average per-hectare total emissions, N_2O for 5-10%, and CH_4 for 5-10%. In the case of RLW and RHW production systems, most emissions were from N-fertilizer application, which represented about 39% and 38%, respectively, of average per-hectare total emissions, closely followed by fertilizer production, with 34% and 28%, and then diesel for field operations (9% and 10%), CO_2 from urea application (7% and 9%), hybrid seed (7%), and pesticides (5% and 4%). Consequently, average per-hectare total emissions from RLW and RHW production systems split almost equally between direct and indirect emission sources and had the following composition: 54% CO_2, 43% N_2O, and 3% CH_4.

Average per-hectare total emissions from irrigated production systems were calculated using national weighted average of the electricity and diesel inputs for irrigation pumping. In SLW production system, most emissions were related to N-fertilizer application, with about 31% and 30% of average per-hectare total emissions for S-S and A-W seasons, respectively, fertilizer production, with 25% and 28%, and generation of electricity for irrigation, with 21% and 28%. Similarly, in SHW production system, the main sources of emissions were N-fertilizer application, with 36% and 41% of average per-hectare total emissions for S-S and A-W seasons, respectively, fertilizer production, with 27% and 32%, and diesel for field work, with 9% and 10%. Therefore, in SLW production system indirect emission sources together comprised the largest proportion of average per-hectare total emissions while in SHW production system, per-hectare total emissions divided almost half-and-half between direct and indirect emission sources. By type of GHG, average per-hectare total emissions from SLW production system were composed of about 67% CO_2, 30% N_2O, and 3% CH_4 while those from SHW production system consisted of about 55% CO_2, 41% N_2O, and 4% CH_4.

In PHW production system, generation of electricity for irrigation was the major contributor, with about 38% of average per-hectare total emissions estimated for the S-S season and 65% of that for the A-W season, followed by N-fertilizer application, with 23% and 7%, respectively, and fertilizer production, with 20% and 6%. As a result, indirect emission sources dominated the emission budget of PHW production system in both growing seasons. Breakdown of average per-hectare total emissions from PHW production system by type of GHG was as follows: 71% CO_2, 25% N_2O, and 4% CH_4 for the S-S season and 87% CO_2, 9% N_2O, and 4% CH_4 for the A-W season.

Uncertainties in the mean values of per-hectare total energy use, *CExC*, and GHG emissions as well as in those of the selected indicators are summarized in Table 5.

3.4 Country-scale estimates

National grain maize planted area was estimated at about 6.2 million ha, comprising more than two million farms that produced around 17.7 million tons of grain in cropping year 2006-2007. Rain-fed production systems represented approximately 85% of total grain maize planted area. In particular, RLWO production system alone accounted for more than half of total planted area, spatially concentrated in the south-southeast Mexican states (Tables A17 and A18). Both RLW and RHW production systems represented about one-third of total maize planted area, located mainly in the central region of the country. Maize area under irrigation constituted only about 15% of total maize planted area, most of which is under SHW, SLW, and SLWO production systems in the central and northern Mexican states. Pressurized irrigated production systems accounted for only about 2% of total maize planted area, with a dominant role of PHW production system in the central-west and northeast regions of the country. Collectively, the maize production systems investigated comprise around 5.8 million ha, that is, about 93% of estimated total maize planted area.Based on average per-hectare total energy use, *CExC*, and GHG emissions estimated for each maize production system, country-scale energy use was computed to be about 40.5 PJ, *CExC* about 49.2 PJ, and GHG emissions around 4.0 Tg CO_2e. Relative contribution of production systems to country-scale total energy use was calculated as follows: RLW 31%, SHW 21%, RLWO 18%, RHW 17%, PHW 7%, SLW 6%, and RHWO <1%. Indirect energy inputs accounted for the greatest proportion of country-scale total energy use (about 68%), mostly because of the large energy embodied in synthetic fertilizers. For country-scale *CExC*, relative shares of production systems were as follows: RLW

33%, SHW 21%, RHW 17%, RLWO 15%, PHW 8%, SLW 6%, and RHWO <1%. Indirect exergetic inputs were also the major contributor (about 74%) to country-scale *CExC* largely due to fertilizer production. Relative contribution of production systems to country-scale total GHG emissions was estimated to be: RLW 34%, SHW 24%, RHW 18%, RLWO 12%, PHW 6%, SLW 6%, and RHWO <1%. Country-scale total GHG emissions divided almost equally between direct (55%) and indirect (45%) emission sources due to the prominent role of emissions from the production and application of synthetic fertilizers. The breakdown of country-scale emissions by type of gas was as follows: 61% CO_2, 36% N_2O, and 3% CH_4.

4. Discussion

Due to limited use of farming inputs, both RLWO and RHWO production systems have the lowest average per-hectare total energy use and *EI* as well as the highest average *ER* of all production systems examined. Thus, from an energy perspective, RLWO and RHWO production systems appear as the most efficient ones. Nevertheless, they also show the lowest average *NE* due to poor grain productivity per unit of land. Note that most energy use in RLWO and RHWO production systems relates to diesel for field operations so variability in this input may largely explain the differences in per-hectare total energy use across locations. Average *ER* of RLWO production system is similar to that reported for traditional maize in Mexico (10.7 - 16.0) and far greater than that recorded for traditional maize production in other developing countries (3.1 - 4.8) [48,60]. However, in both RLWO and RHWO production systems most energy derives from diesel with a marginal contribution of human and animal energy whereas traditional maize production is reported to rely heavily on animate energy [14,16,48,60]. Thus, RLWO and RHWO production systems may rather represent production systems in transition from traditional to more mechanized production, a conversion process that has been observed in some formerly rural communities in Mexico [61].

Average per-hectare total energy use of RLW and RHW production systems more than doubles that of their unfertilized counterparts mainly due to the large energy embodied in synthetic fertilizers. However, higher per-hectare energy inputs are offset to some degree by higher yields, resulting in greater average *NE* of both RLW and RHW production systems. Differences in fertilizer application rates are probably the main cause of variation in per-hectare total energy use across Mexican states. In general, locations with the highest fertilizer application rates record the highest yields and thus, achieve comparatively greater *NE* and lower *EI*. For instance, heavily fertilized RHW production system in Jalisco and Guanajuato states shows comparable performance to that of high-input rain-fed maize systems in the U.S., which have *EI* in the range 2.1 - 3.3 GJ Mg^{-1} of grain [28].

Average per-hectare total energy use of irrigated production systems is about 2 to 4 times greater than that of their rain-fed counterparts, largely due to increased fertilizer application rates and extra energy for irrigation. Irrigated production systems also have greater average *NE* due to higher yields, which also contribute to moderate the rise in average *EI* relative to the other production systems examined. Among all irrigated production systems, SHW production system exhibits the best scores in average *EI*, *NE*, and *ER* because of its superior grain yields. Note that SHW production system benefits from both gravity-fed irrigation and low reliance on groundwater to reduce greatly the energy requirements for irrigation [32]. Nevertheless, performance of SHW production system seems far from that of high-input irrigated maize in the U.S., which achieves much higher yield (13.2 Mg ha^{-1} on average) and *NE* (159.0 GJ ha^{-1}) [12]. Even though average per-hectare total energy use of PHW production system is greater than that of the surface-irrigated production systems, grain yields of the former do not increase in the same proportion, resulting in PHW production system having the highest average *EI* and the lowest average *ER* among all production systems. This indicates that PHW production system may use the energy more inefficiently than the other production systems.

Comparisons of *CExC*-based indicators between the selected production systems in general parallel comparisons of energy-based indicators because both energy use and exergy consumption accounting yielded similar results. The similarity of results may be due to the particular characteristics of the agriculture production process as differences between energy and exergy analyses tend to be more apparent when examining industrial processes. Reported *CExC* in maize production varies from 27.8 GJ ha^{-1} (4.4 GJ Mg^{-1}) in Canada [24] to 39.6 GJ ha^{-1} (4.6 GJ Mg^{-1}) in the U.S. [23] to 51.9 GJ ha^{-1} (10.5 GJ Mg^{-1}) in China [25]. In all cases, synthetic fertilizers hold the largest share of total *CExC* (40-70%), in agreement with the present study. Differences with values calculated here could be attributed to greater fertilizer application rates and additional fuel for post-harvest operations. The results from *CExC* analysis underscore that both production of synthetic fertilizers and generation of electricity for irrigation demand a substantial flow of natural resources. Thus, improved efficiency in producing and using fertilizers and electricity could greatly contribute to enhance the sustainability of maize production systems.

With regard to GHG emissions, RLWO and RHWO production systems have the smallest average per-hectare total emissions and *GHGI* as well as the first and third lowest $GHGE_i$ among all production systems due mainly to low-level use of farming inputs. Both RLW and RHW production systems generate more emissions per hectare than their unfertilized counterparts, largely because of added emissions from synthetic fertilizer production and use. However, average *GHGI* of RLW and RHW production systems increases modestly as higher emissions per unit area are counterbalanced by higher grain yields. The prominent role of emissions from fertilizer production and use is in line with findings of studies conducted on maize production in the U.S. [28] and Canada [62]. Irrigation pumping and higher fertilizer rates are responsible for most of the increase in average per-hectare total emissions from SLW and SHW production systems relative to their rain-fed counterparts. However, due to their superior productivity, average *GHGI* of surface-irrigated production systems are among the lowest of all production systems. In particular, the performance of SHW production system in Sinaloa State compares favorably with that of high-input, high-yield irrigated maize systems in the U.S. in relation to total emissions per unit area (3,000.0 kg CO_2e ha^{-1}) and per unit of grain (231.0 kg CO_2e Mg^{-1}) [12]. The PHW production system records the highest average per-hectare total emissions and *GHGI* owing to the combination of large emissions from irrigation pumping and small increase in average yield relative to the other production systems. The greatest average $GHGE_i$ corresponds to SHW, RLW and RHW production systems largely because of their heavy use of farming inputs with high embodied energy-related emissions, particularly N-fertilizers. Note that due to input data limitations, other emission sources (e.g. crop residue decomposition, indirect N_2O emissions, etc.) were not quantified and so calculated GHG emissions may be underestimated.

The relevance of synthetic fertilizers in total energy use, *CExC* and GHG emissions emphasizes the role of fertilizer use efficiency in the resource use and environmental performance of maize farming. Global estimates indicate that only about 30-50% of applied N fertilizer, 10-45% of P fertilizer, and 20-40% of K fertilizer is taken up by field crops [63,64]. Compiled data are insufficient to derive detailed information on this particular aspect of the maize production systems in Mexico though, fertilizer use efficiency is likely to be low because over-fertilization is a common practice in Mexican crop production, especially in high-input production systems [65]. Thus, adopting improved fertilizer management practices could reduce the amount of synthetic fertilizers applied and hence, contribute to minimize the energy, *CExC* and GHG footprints of maize production.

In general, uncertainties in the estimates are considerable due to (i) the limited number of Mexican states with available information and (ii) the great variability in input use intensities, primarily those of diesel for field operations, fertilizers, and pesticides. Moreover, fluctuations in grain yields within production systems introduced additional uncertainty in average *EI*, *NE*, *ER*, *ExI*, *NEx*, *ExR*, and *GHGI*. Estimates could be refined by, for instance, conducting separate analysis for geographical regions where maize management practices are somewhat homogenous.

Annual final energy use in the Mexican agriculture sector in 2006-2007 period averaged around 130.0 PJ, mostly supplied by diesel (74%) and electricity (22%) [56]. Note that this figure comprises only on-farm energy use and hence, represents the direct energy inputs to agriculture activities. Based on this figure, estimated country-scale direct energy use in the selected maize production systems (about 13.0 PJ) would represent only about 10% of total final energy use in the agriculture sector. Similarly, estimated country-scale GHG emissions from direct energy use (about 870.0 Gg CO_2e) and fertilizer application (1,530.0 Gg CO_2e) in the maize production systems investigated would account for about 7% of national GHG emissions from agricultural energy use (about 12,266 Gg CO_2e) and 22% of those from agricultural soils (6,969 Gg CO_2e) reported for 2006 [66]. Country-level data on indirect energy use and GHG emissions from agriculture activities are currently unavailable. Relatively small shares of estimated energy use and GHG emissions from maize production in total agricultural energy use and GHG emissions seem reasonable given the prominent role of low- and medium-input maize production systems in terms of planted area.

5. Conclusions

Total energy use, cumulative exergy consumption, and GHG emissions were computed for seven different maize production systems. Estimates vary widely within and across production systems largely due to differences in the type and amount of farming inputs applied and field operations performed as well as in grain yields achieved, which to some degree reflect the diversity of agro-ecological and socio-economic conditions affecting maize production in Mexico.

Diesel for field operations, synthetic fertilizer production and use, and generation of electricity for irrigation pumping are the major contributors to total energy use, exergy consumption, and GHG emissions from maize farming. Low-input rain-fed production systems, which comprise the largest proportion of total maize area, exhibit low total energy use, exergy consumption and GHG emissions on a land area basis though, in general they achieve low yields and so require large pieces of arable land to produce sizable amounts of grain. By contrast, high-input production systems record much greater per-hectare total energy use, exergy consumption, and GHG emissions due mainly to heavy use synthetic fertilizers and irrigation pumping. However, as these production systems also achieve superior yields, the resource use and environmental burdens per unit of harvested grain are at intermediate levels. Reducing diesel use in mechanical field operations, improving synthetic fertilizer and irrigation use efficiency, and switching to organic fertilizers and alternative sources of energy for irrigation pumping could potentially enhance the sustainability of maize production systems. Appropriate adjustments in management practices and policy interventions to promote those modifications should be the focus of future work. Possible options to boost the yields of low-input production systems and improve the input use efficiency of intensive production systems in a sustainable fashion should also be explored in subsequent studies. Besides, given that estimates rest on secondary data, due to time and resource constraints for collecting data directly from maize farms across the country, they need corroboration by field measurements. Results of the present study can be employed as input data to conduct energy, exergy, and GHG emissions analyses of the industrial maize products with a life-cycle approach.

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Figure captions

Figure 1. System boundaries showing the direct and indirect energy and exergetic inputs and GHG emission sources considered. (*Human labor and animal labor accounted only for as direct energy inputs. **GHG emissions from electricity generation taken as an indirect emission source.)

[1.5 column figure]

Figure 2. Average per-hectare total energy use of the selected maize production systems and contribution of the different energy inputs. S-S, spring-summer growing season; A-W, autumn-winter growing season. R, rain-fed; S, surface irrigated; P, pressurized irrigated; L, landrace seed; H, hybrid seed; WO, without synthetic fertilizers; W, with synthetic fertilizers; T&D, transportation and distribution. Labor includes human labor and animal labor. Farm machinery includes irrigation equipment. Bars with line patterns represent direct energy inputs. Bars with solid colors represent indirect energy inputs.

[2 column figure]

Figure 3. Average per-hectare cumulative exergy consumption (*CExC*) of the selected maize production systems and contribution of the different exergetic inputs. S-S, spring-summer growing season; A-W, autumn-winter growing season. R, rain-fed; S, surface irrigated; P, pressurized irrigated; L, landrace seed; H, hybrid seed; WO, without synthetic fertilizers; W, with synthetic fertilizers; T&D, transportation and distribution. Farm machinery includes irrigation equipment. Bars with line patterns represent direct exergetic inputs. Bars with solid colors represent indirect exergetic inputs.

[2 column figure]

Figure 4. Average per-hectare total greenhouse gas (GHG) emissions of the selected maize production systems and contribution of the different emission sources. S-S, spring-summer growing season; A-W, autumn-winter growing season; R, rain-fed; S, surface irrigated; P, pressurized irrigated; L, landrace seed; H, hybrid seed; WO, without synthetic fertilizers; W, with synthetic fertilizers; T&D, transportation and distribution. Farm machinery includes irrigation equipment.

Bars with line patterns represent direct emission sources. Bars with solid colors represent indirect emission sources.

[2 column figure]

Figure 1

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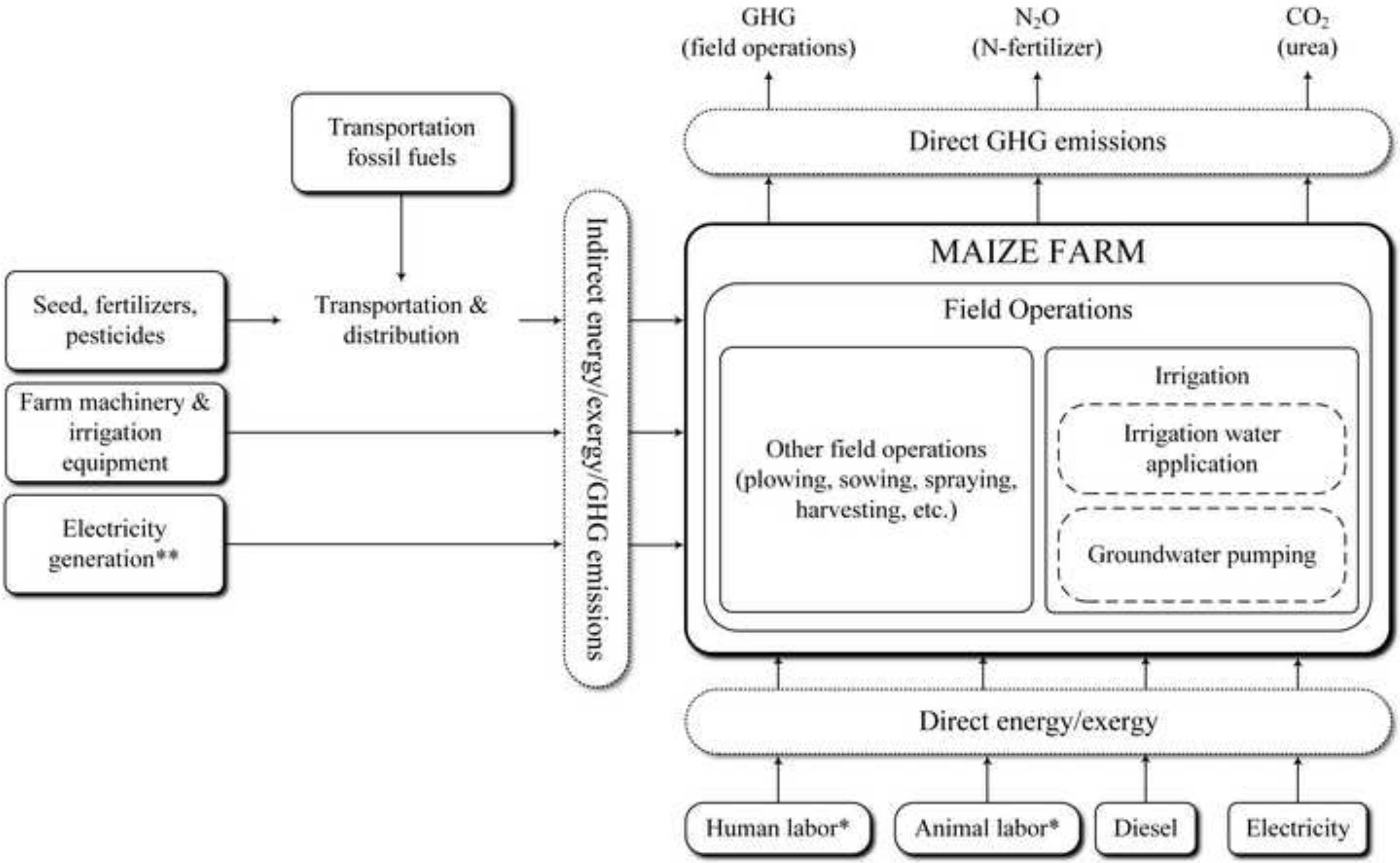


Figure 2

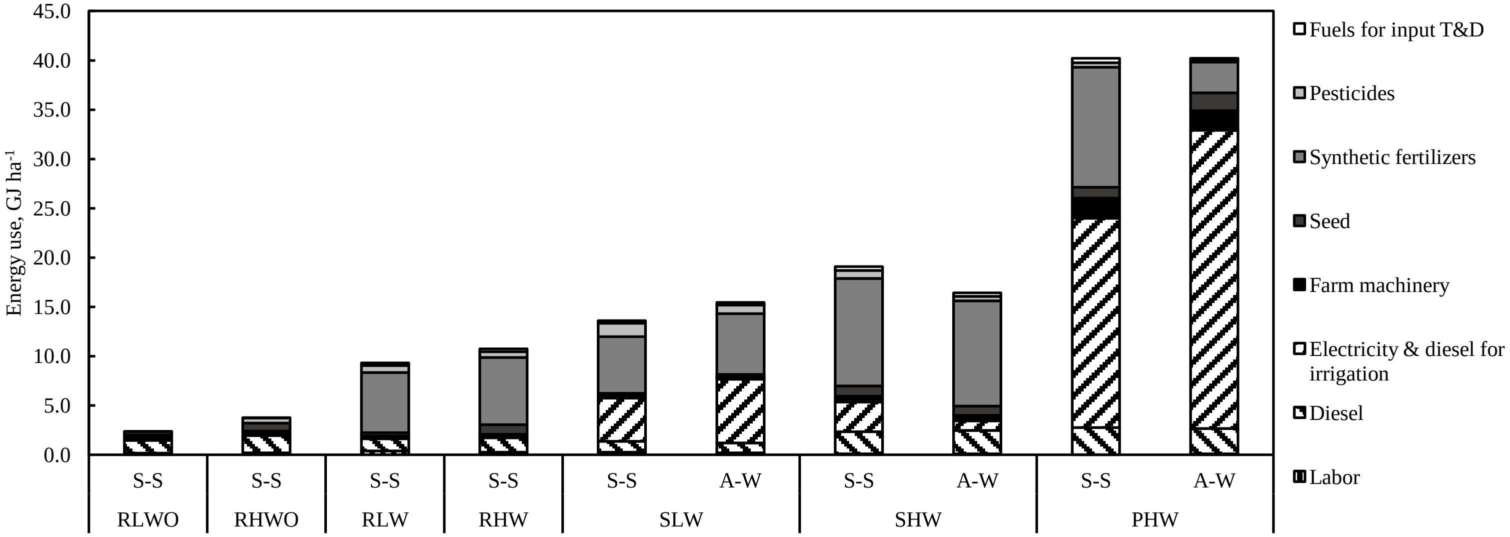
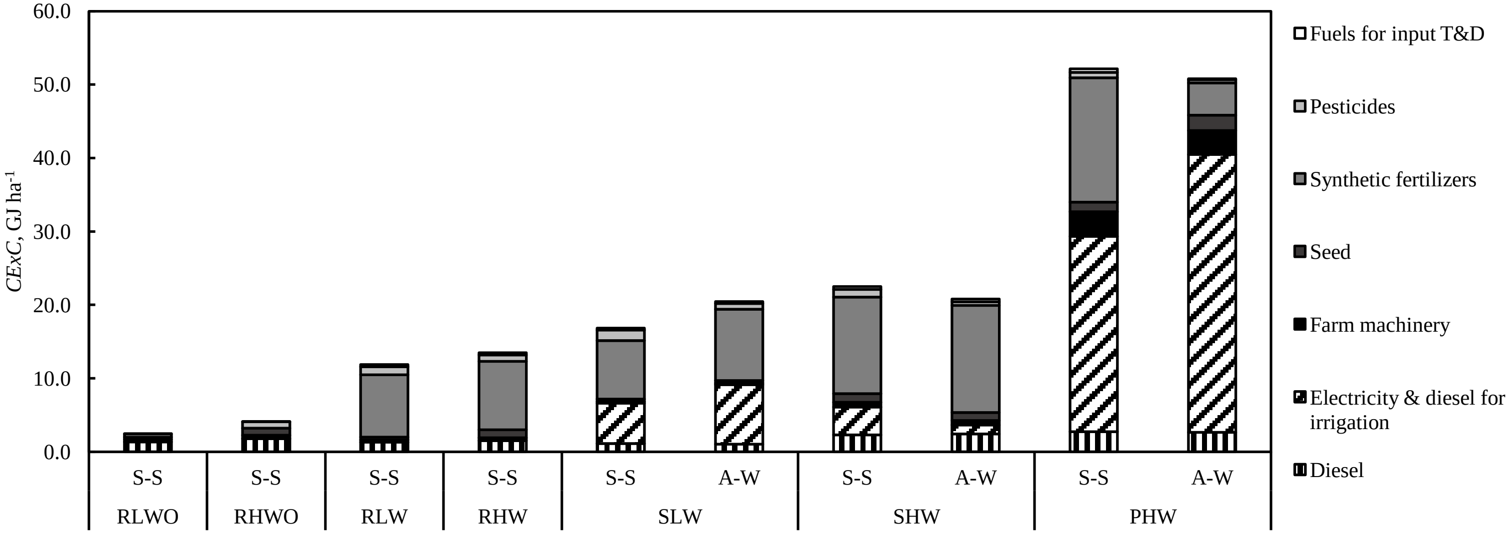
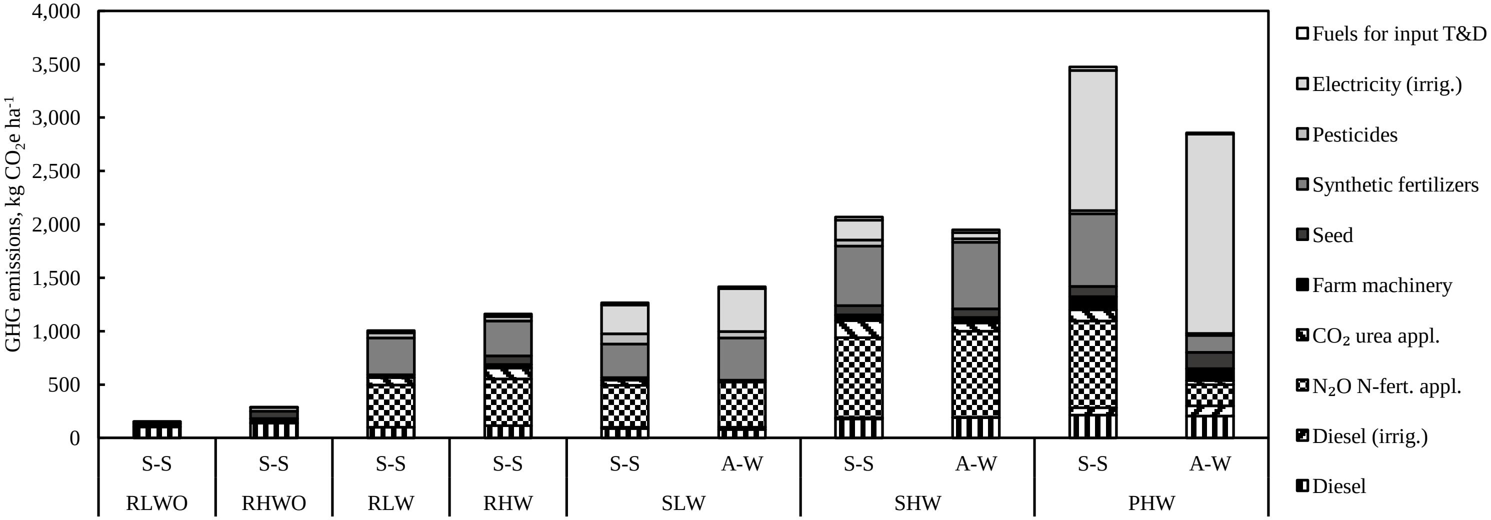

45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Energy use, GJ ha^{-1}
S-S
S-S
S-S
S-S
S-S
A-W
S-S
A-W
S-S
A-W
RLWO
RHWO
RLW
RHW
SLW
SHW
PHW
Fuels for input T&D
Pesticides
Synthetic fertilizers
Seed
Farm machinery
Electricity & diesel for irrigation
Diesel
Labor

Figure 3



60.0
50.0
40.0
30.0
20.0
10.0
0.0
CExC, GJ ha-1
S-S
S-S
S-S
S-S
S-S
A-W
S-S
A-W
S-S
A-W
RLWO
RHWO
RLW
RHW
SLW
SHW
PHW
Fuels for input T&D
Pesticides
Synthetic fertilizers
Seed
Farm machinery
Electricity & diesel for irrigation
Diesel

Figure 4



4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
GHG emissions, kg CO_2e ha^{-1}
S-S
S-S
S-S
S-S
S-S
A-W
S-S
A-W
S-S
A-W
RLWO
RHWO
RLW
RHW
SLW
SHW
PHW
Fuels for input T&D
Electricity (irrig.)
Pesticides
Synthetic fertilizers
Seed
Farm machinery
CO_2 urea appl.
N_2O N-fert. appl.
Diesel (irrig.)
Diesel

Table 1

Table 1. Maize production systems based on cropping systems typology developed by [31].

Production system	Description
RLWO	Rain-fed, landrace seed, without fertilizers
RLW	Rain-fed, landrace seed, with fertilizers
RHWO	Rain-fed, hybrid seed, without fertilizers
RHW	Rain-fed, hybrid seed, with fertilizers
SLWO	Surface irrigated, landrace seed, without fertilizers
SLW	Surface irrigated, landrace seed, with fertilizers
SHWO	Surface irrigated, hybrid seed, without fertilizers
SHW	Surface irrigated, hybrid seed, with fertilizers
PLWO	Pressurized irrigated, landrace seed, without fertilizers
PLW	Pressurized irrigated, landrace seed, with fertilizers
PHWO	Pressurized irrigated, hybrid seed, without fertilizers
PHW	Pressurized irrigated, hybrid seed, with fertilizers

Table 2

Table 2. Range and mean value of estimated per-hectare total energy use, relative shares of direct and indirect energy inputs, energy intensity (*EI*), net energy (*NE*), and energy output-input ratio (*ER*) of the selected maize production systems.

Production system[a]	Season[b]	Total energy use		Direct inputs[e]		Indirect inputs[g]		*EI*		*NE*		*ER*	
		[GJ ha^{-1}]		[%]		[%]		[GJ Mg^{-1} of grain]		[GJ ha^{-1}]			
		Range[c]	Mean[d]	Range	Mean[f]	Range	Mean[f]	Range	Mean[d]	Range	Mean[d]	Range	Mean[d]
RLWO	S-S	1.38 - 3.70	2.35	46 – 77	63	23 – 54	37	0.50 - 3.42	1.75	11.12 - 36.36	20.57	4.01 - 27.29	12.03
RHWO	S-S	3.02 - 4.32	3.75	46 – 58	52	42 – 54	48	2.02 - 2.88	2.58	15.04 - 17.56	16.29	4.76 - 6.81	5.48
RLW	S-S	5.83 - 14.89	9.32	11 – 39	18	61 – 89	82	2.11 - 6.54	4.24	13.89 - 32.52	22.12	2.10 - 6.50	3.81
RHW	S-S	4.51 - 26.60	10.75	7 – 33	16	67 – 93	84	2.14 - 7.39	3.95	8.53 - 51.82	28.23	1.86 - 6.42	4.07
SLW	S-S	3.77 - 20.76	13.61	14 – 43	42	57 – 86	58	0.94 - 4.28	3.58	29.72 - 51.13	39.69	3.21 - 14.55	4.45
	A-W	-	15.44	-	50	-	50	-	5.15	-	25.74	-	2.67
SHW	S-S	10.35 - 48.57	19.08	7 – 62	28	38 – 93	72	1.53 - 6.12	2.92	43.97 - 92.41	73.14	2.24 - 8.97	5.45
	A-W	10.83 - 42.27	16.42	13 – 73	21	27 – 87	79	2.06 - 12.69	3.22	3.44 - 106.75	57.07	1.08 - 6.67	4.49
PHW	S-S	22.75 - 63.58	40.23	42 – 80	60	20 – 58	40	4.12 - 7.61	6.35	32.15 - 85.95	52.78	1.80 - 3.33	2.30
	A-W	22.57 - 45.94	40.20	57 – 86	82	14 – 43	18	5.05 - 7.32	8.45	32.33 - 40.25	27.41	1.88 - 2.72	1.68

[a] R, rain-fed; S, surface irrigated; P, pressurized irrigated, L, landrace seed; H, hybrid seed; WO, without synthetic fertilizers; W, with synthetic fertilizers. [b] S-S, spring-summer; A-W, autumn-winter. [c] Minimum and maximum of estimated values. [d] Simple average of state-level per-hectare total energy use except for irrigated production systems for which national weighted average (by planted area) of irrigation energy inputs were used instead of state-level irrigation energy inputs. [e] Human and animal labor, diesel for field operations, and electricity and diesel for irrigation pumping. [f] Relative shares in average per-hectare total energy use. [g] Manufacture of farm machinery, irrigation equipment, seed, synthetic fertilizers, and pesticides as well as fuels consumed for input transportation and distribution.

Table 3

Table 3. Range and mean value of estimated per-hectare cumulative exergy consumption (*CExC*), relative shares of direct and indirect exergetic inputs, exergy intensity (*ExI*), net exergy (*NEx*), and exergy output-input ratio (*ExR*) of the selected maize production systems.

Production system[a]	Season[b]	*CExC*		Direct inputs[e]		Indirect inputs[g]		*ExI*		*NEx*		*ExR*	
		[GJ ha^{-1}]		[%]		[%]		[GJ Mg^{-1} grain]		[GJ ha^{-1}]			
		Range[c]	Mean[d]	Range	Mean[f]	Range	Mean[f]	Range	Mean[d]	Range	Mean[d]	Range	Mean[d]
RLWO	S-S	1.48 - 4.17	2.46	32 – 72	54	28 – 68	46	0.54 - 3.86	1.85	13.40 - 43.27	24.72	4.21 - 30.12	14.08
RHWO	S-S	3.14 - 4.89	4.12	41 – 46	43	54 – 59	57	2.09 - 3.26	2.83	18.12 - 21.27	19.64	5.00 - 7.77	5.98
RLW	S-S	6.34 - 19.52	11.86	5 – 36	11	64 – 95	89	3.28 - 8.12	5.30	16.58 - 36.20	25.43	2.00 - 4.96	3.43
RHW	S-S	5.16 - 30.24	13.51	4 – 29	11	71 – 96	89	2.64 - 8.40	4.94	10.30 - 60.53	32.71	1.94 - 6.17	3.69
SLW	S-S	4.30 - 24.93	16.85	7 – 39	39	61 – 93	61	1.08 - 5.14	4.48	33.75 - 60.80	46.35	3.17 - 15.13	4.31
	A-W	-	20.45	-	45	-	55	-	6.82	-	28.38	-	2.39
SHW	S-S	12.19 - 57.99	22.51	4 – 62	27	38 – 96	73	1.80 - 7.18	3.46	52.63 - 109.93	86.84	2.27 - 9.03	5.53
	A-W	13.21 - 53.47	20.80	9 – 71	17	29 – 91	83	2.38 - 16.06	4.13	0.73 - 127.10	66.34	1.01 - 6.82	4.25
PHW	S-S	29.07 - 80.00	52.13	35 – 78	56	22 – 65	44	5.54 - 9.41	8.17	36.03 - 92.58	58.16	1.73 - 2.94	2.10
	A-W	26.91 - 57.66	50.81	57 – 84	80	16 - 43	20	5.98 - 9.18	10.71	34.70 - 46.33	29.37	1.77 - 2.72	1.58

[a] R, rain-fed; S, surface irrigated; P, pressurized irrigated, L, landrace seed; H, hybrid seed; WO, without synthetic fertilizers; W, with synthetic fertilizers. [b] S-S, spring-summer; A-W, autumn-winter. [c] Minimum and maximum of estimated values. [d] Simple average of state-level per-hectare *CExC* except for irrigated production systems for which national weighted average (by planted area) of irrigation energy inputs were used instead of state-level irrigation energy inputs. [e] Diesel for field operations and electricity and diesel for irrigation pumping. [f] Relative shares in average per-hectare *CExC*. [g] Manufacture of farm machinery, irrigation equipment, seed, synthetic fertilizers and pesticides as well as fuels consumed for input transportation and distribution.

Table 4

Table 4. Range and mean value of estimated per-hectare total greenhouse gas (GHG) emissions, relative shares of direct and indirect GHG emission sources, GHG emission intensity (*GHGI*), and GHG emissions per unit input energy (*$GHGE_i$*) of the selected maize production systems.

Production system[a]	Season[b]	GHG emissions		Direct sources[e]		Indirect sources[g]		*GHGI*		*GHGEi*	
		[kg-CO$_2$e ha^{-1}]		[%]		[%]		[kg-CO$_2$e Mg^{-1} grain]		[kg-CO$_2$e GJ^{-1}]	
		Range[c]	Mean[d]	Range	Mean[f]	Range	Mean[f]	Range	Mean[d]	Range	Mean[d]
RLWO	S-S	72.48 - 264.43	152.91	50 - 82	68	18 - 50	32	26.36 - 244.84	116.53	52.41 - 71.49	63.06
RHWO	S-S	213.24 - 341.19	286.68	45 - 51	49	49 - 55	51	142.16 - 227.46	197.03	70.52 - 78.91	75.92
RLW	S-S	554.05 - 1,589.29	1,005.71	43 - 67	56	33 - 57	44	223.23 – 737.98	452.82	94.79 - 129.00	106.81
RHW	S-S	377.76 - 3,398.09	1,160.06	23 - 69	56	31 - 77	44	157.40 - 943.91	417.44	73.62 - 127.77	103.76
SLW	S-S	353.34 – 1,985.02	1,264.59	44 - 67	43	33 - 56	57	88.34 – 409.28	332.30	93.72 – 110.53	90.36
	A-W	-	1,415.26	-	37	-	63	-	471.75	-	91.67
SHW	S-S	870.46 – 4,382.21	2,068.50	36 - 59	53	41 - 64	47	128.77 – 578.87	317.07	84.10 – 123.48	106.41
	A-W	1,089.49 – 3,649.39	1,949.75	24 - 62	55	38 - 76	45	217.90 – 1,095.91	380.37	86.34 – 128.96	117.20
PHW	S-S	2,032.75 – 4,709.13	3,475.78	23 - 43	35	57 - 77	65	371.71 – 673.27	545.11	74.08 – 100.18	86.04
	A-W	1,709.44 – 3,161.49	2,855.76	14 - 44	19	56 - 86	81	379.87 – 503.42	601.86	68.82 – 76.12	70.97

[a] R, rain-fed; S, surface irrigated; P, pressurized irrigated, L, landrace seed; H, hybrid seed; WO, without synthetic fertilizers; W, with synthetic fertilizers. [b] S-S, spring-summer; A-W, autumn-winter. [c] Minimum and maximum of estimated values. [d] Simple average of state-level per-hectare total GHG emissions except for irrigated production systems for which national weighted average (by planted area) of irrigation energy-related GHG emissions were used instead of state-level irrigation energy-related GHG emissions. [e] Diesel for field operations, diesel for irrigation pumping, direct N_2O emissions from N-fertilizer application, and CO_2 emissions from urea application. [f] Relative shares in average per-hectare total GHG emissions. [g] Manufacture of farm machinery, irrigation equipment, seed, synthetic fertilizers and pesticides as well as fossil fuels consumed for input transportation and distribution and generation of electricity for irrigation.

Table 5

Table 5. Estimated per-cent uncertainty in mean values of per-hectare total energy use, energy intensity (*EI)*, net energy (*NE*), energy output-input ratio (*ER*), per-hectare cumulative exergy consumption (*CExC*), exergy intensity (*ExI*), net exergy (*NEx*), exergy output-input ratio (*ExR*), per-hectare total greenhouse gas (GHG) emissions, GHG emission intensity (*GHGI*), and GHG emissions per unit input energy ($GHGE_i$) of the selected maize production systems.

Production system[a]	Growing season[b]	Energy use	*EI*	*NE*	*ER*	*CExC*	*ExI*	*NEx*	*ExR*	GHG emissions	*GHGI*	*GHGEi*
RLWO	S-S	±12%	±22%	±20%	±22%	±13%	±22%	±20%	±22%	±14%	±23%	±19%
RHWO	S-S	±8%	±8%	±4%	±8%	±7%	±8%	±4%	±8%	±8%	±8%	±11%
RLW	S-S	±13%	±15%	±12%	±15%	±13%	±15%	±13%	±15%	±10%	±13%	±16%
RHW	S-S	±13%	±16%	±15%	±16%	±12%	±15%	±15%	±15%	±11%	±15%	±17%
SLW	S-S	±19%	±24%	±22%	±24%	±20%	±25%	±22%	±25%	±17%	±23%	±25%
	A-W[c]	-	-	-	-	-	-	-	-	-	-	-
SHW	S-S	±10%	±11%	±7%	±11%	±10%	±11%	±7%	±11%	±8%	±9%	±12%
	A-W	±11%	±17%	±18%	±17%	±10%	±17%	±18%	±17%	±9%	±16%	±14%
PHW	S-S	±4%	±13%	±21%	±13%	±5%	±13%	±23%	±13%	±5%	±13%	±6%
	A-W	±4%	±15%	±35%	±15%	±4%	±15%	±39%	±15%	±5%	±15%	±7%

[a] R, rain-fed; S, surface irrigated; P, pressurized irrigated, L, landrace seed; H, hybrid seed; WO, without synthetic fertilizers; W, with synthetic fertilizers. [b] S-S, spring-summer; A-W, autumn-winter. [c] No uncertainties were calculated because data were only available for one Mexican state.

Assessing maize production systems in Mexico from an energy, exergy, and greenhouse-gas emissions perspective

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Supplemental Tables and Figures

Table A1. Maize production systems and Mexican states for which maize grain production costs data from [1] were used.

Production system[a]	S-S growing season[b]	A-W growing season[c]
RLWO	Guanajuato (Gto), Guerrero (Gro), Nuevo León (NL), Oaxaca (Oax), San Luis Potosí (SLP), Tabasco (Tab)	
RHWO	Aguascalientes (Ags), Oaxaca (Oax), Tabasco (Tab)	
RLW	Chihuahua (Chih), Guanajuato (Gto), Guerrero (Gro), México (Mex), Michoacán (Mich), Oaxaca (Oax), Tlaxcala (Tlax), Veracruz (Ver)	
RHW	Aguascalientes (Ags), Chiapas (Chis), Chihuahua (Chih), Durango (Dgo), Guanajuato (Gto), Guerrero (Gro), Jalisco (Jal), México (Mex), Michoacán (Mich), Morelos (Mor), Oaxaca (Oax), Tabasco (Tab), Tlaxcala (Tlax), Yucatán (Yuc)	
SLW	Guerrero (Gro), Michoacán (Mich), Nuevo León (NL)	Guerrero (Gro)
SHW	Aguascalientes (Ags), Chihuahua (Chih), Durango (Dgo), Guanajuato (Gto), Guerrero (Gro), Jalisco (Jal), Michoacán (Mich), Sinaloa (Sin)	Colima (Col), Guerrero (Gro), Michoacán (Mich), Nuevo León (NL), Sinaloa (Sin), Sonora (Son), Tamaulipas (Tamps)
PHW	Aguascalientes (Ags), Chihuahua (Chih), Guanajuato (Gto), Michoacán (Mich), Nuevo León (NL), Tlaxcala (Tlax)	Baja California Sur (BCS), Guerrero (Gro), Tamaulipas (Tamps)

[a] R, rain-fed; S, surface irrigated; P, pressurized irrigated; L, landrace seed; H, hybrid seed; WO, without synthetic fertilizers; W, with synthetic fertilizers. [b] S-S, spring-summer. [c] A-W, autumn-winter. State abbreviation is given (in parentheses).

Table A2. Range and mean value of per-hectare farming input rates of the rain-fed maize production systems. Based on data from [1] for the spring-summer growing season.

Farming input	Unit	RLWO production system		RHWO production system		RLW production system		RHW production system	
		Range[a]	Mean (SD)[b]	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)
Seed	[kg]	15.0 - 20.0	18.3 (2.1)	15.0 - 20.0	18.3 (2.9)	18.3 - 23.3	22.0 (1.9)	12.0 - 40.0	21.3 (6.6)
Diesel[c]	[L]	10.7 - 45.4	30.3 (13.5)	31.8 - 45.4	40.8 (7.8)	11.9 - 52.1	29.4 (12.8)	18.1 - 58.2	34.1 (12.4)
Human labor[d]	[hours]	30.0 – 133.0	85.8 (44.3)	30.0 – 144.0	87.3 (57.0)	32.0 – 180.7	105.8 (42.8)	14.0 – 344.0	127.9 (86.5)
Animal labor[e]	[hours]	-	-	-	-	0.0 – 44.0	13.2 (19.1)	0.0 – 24.0	2.7 (6.8)
N[f]	[kg]	-	-	-	-	33.8 - 142.0	84.4 (41.7)	0.1 - 315.0	93.5 (80.6)
P (as P_2O_5)[f]	[kg]	-	-	-	-	27.3 - 162.9	59.8 (44.7)	26.7 - 92.0	54.1 (20.0)
K (as K_2O)[f]	[kg]	-	-	-	-	0.0 - 68.0	9.0 (23.9)	0.0 - 85.0	12.8 (26.6)
Herbicides	[kg]	0.0 - 1.5	0.3 (0.6)	0.0 - 1.5	0.5 (0.9)	0.0 - 3.0	0.4 (1.0)	0.0 - 1.0	0.1 (0.3)
	[L]	0.0 - 2.5	0.9 (1.1)	0.0 - 2.5	1.2 (1.3)	0.0 - 6.7	1.9 (2.1)	0.3 - 6.0	2.5 (1.6)
Insecticides	[kg]	0.0 - 12.0	2.8 (4.9)	0.0 - 12.0	4.5 (6.5)	0.0 - 28.0	6.6 (10.3)	0.0 - 26.7	6.1 (9.4)
	[L]	0.0 - 2.0	0.7 (0.8)	0.0 - 2.0	1.0 (1.0)	0.0 - 2.7	0.7 (0.9)	0.0 - 3.1	0.8 (0.8)
Other pesticides	[kg]	-	-	-	-	0.0 - 1.3	0.2 (0.5)	0.0 - 0.8	0.1 (0.2)
	[L]	-	-	-	-	-	-	0.0 - 0.4	<0.1 (0.1)
Grain yield	[Mg ha^{-1}]	1.0 - 2.8	1.7 (0.7)	1.4 - 1.5	1.5 (0.1)	1.5 - 2.8	2.3 (0.5)	1.0 - 5.0	2.8 (1.1)

R, rain-fed; L, landrace seed; H, hybrid seed; W, with synthetic fertilizers; WO, without synthetic fertilizers. [a] Minimum and maximum input rates reported for Mexican states with available data. [b] Simple average and (standard deviation) of reported input rates. [c] Based on estimated diesel use in the mechanical field operations performed. [d] Only for manual field operations. [e] Only for draft animal-powered field operations. [f] Based on N, P_2O_5, and K_2O typical content of applied fertilizers.

Table A3. Range and mean value of per-hectare farming input rates of the irrigated maize production systems. Based on data from [1,2].

		SLW production system				SHW production system				PHW production system			
		S-S growing season		A-W growing season		S-S growing season		A-W growing season		S-S growing season		A-W growing season	
Farming input	Unit	Range[a]	Mean (SD)[b]	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)
Seed	[kg]	15.0 - 25.0	18.3 (5.8)	-	20.0	15.0 - 28.0	22.9 (4.0)	17.1 - 30.0	21.2 (4.1)	20.0 - 30.0	24.7 (3.3)	20.0 - 75.0	40.0 (30.4)
Diesel[c]	[L]	18.1 - 31.9	25.7 (7.0)	-	23.7	26.1 - 79.9	52.5 (19.9)	30.9 - 110.8	55.5 (26.8)	33.1 - 111.0	62.7 (27.5)	13.2 - 101.8	60.1 (44.6)
Human labor[d]	[hours]	39.0 – 352.0	176.3 (160.0)	-	140.0	2.0 – 116.6	44.9 (47.7)	0.0 – 166.0	60.2 (72.5)	0.0 – 76.0	32.9 (29.4)	0.0 – 168.0	56.0 (97.0)
Animal labor[e]	[hours]	0.0 – 5.0	1.7 (2.9)	-	-	-	-	-	-	-	-	0.0 – 16.0	5.3 (9.2)
N[f]	[kg]	23.0 - 138.0	83.7 (57.8)	-	90.0	30.1 - 253.0	160.2 (70.9)	59.9 - 295.0	172.5 (82.6)	103.0 - 273.0	172.9 (61.7)	16.1 - 59.8	41.8 (22.8)
P (as P_2O_5)[f]	[kg]	0.0 - 69.0	46.0 (39.8)	-	69.0	0.0 - 103.5	54.3 (42.8)	0.0 - 103.5	45.2 (36.9)	46.0 - 161.0	102.0 (49.2)	0.0 - 46.0	28.7 (25.0)
K (as K_2O)[f]	[kg]	-	-	-	-	0.0 - 45.0	9.5 (16.4)	0.0 - 30.0	4.3 (11.3)	0.0 - 45.0	7.5 (18.4)	-	-
Herbicides	[kg]	-	-	-	-	0.0 - 0.3	<0.1 (0.1)	-	-	0.0 - 1.0	0.2 (0.4)	-	-
	[L]	2.0 - 6.0	4.0 (2.0)	-	5.0	0.0 - 6.0	2.3 (2.0)	0.0 - 3.0	0.9 (1.1)	0.0 - 2.0	1.4 (0.8)	0.0 - 4.0	1.8 (2.0)
Insecticides	[kg]	0.0 - 80.0	26.7 (46.2)	-	-	0.0 - 29.3	10.1 (11.0)	0.0 - 15.0	2.1 (5.7)	0.0 - 16.5	4.1 (6.7)	-	-
	[L]	0.0 - 1.0	0.3 (0.6)	-	-	0.0 - 10.5	2.0 (3.5)	0.0 - 3.8	1.5 (1.4)	0.0 - 3.0	1.1 (1.2)	0.0 - 1.1	0.7 (0.6)
Other pesticides	[kg]	-	-	-	-	0.0 - 0.3	<0.1 (0.1)	0.0 - 1.0	0.1 (0.4)	0.0 - 0.5	0.1 (0.2)	-	-
	[L]	-	-	-	-	-	-	0.0 - 0.8	0.1 (0.3)	-	-	-	-
Irrigation[g]													
Applied water	[mm]	7.1 – 758.8	209.3 (107.0)	306.6 – 838.7	551.1 (110.1)	7.1 – 758.8	252.1 (98.6)	306.6 – 838.7	521.7 (38.6)	5.7 – 669.8	249.7 (154.8)	255.0 – 738.1	564.3 (80.2)
Human labor	[hours]	-	2.0	-	2.0	-	2.0	-	2.0	0.4 – 2.2	1.6 (0.4)	0.2 – 2.5	1.6 (0.4)
Electricity	[kWh]	0.7 - 3,656.6	424.2 (530.1)	0.0 – 6,488.5	627.9 (1,164.5)	0.0 - 2,736.2	294.7 (508.0)	0.0 - 5,699.2	92.7 (464.2)	19.0 - 4,462.4	2,064.9 (1,594.7)	427.9 – 6,107.4	2,936.3 (1,830.3)
Diesel	[L]	<0.1 – 35.3	4.1 (5.1)	0.0 – 62.6	6.1 (11.2)	0.0 – 26.4	2.9 (4.9)	0.0 – 55.0	0.9 (4.5)	0.2 - 43.1	19.9 (15.4)	4.1 – 58.9	28.3 (17.7)
Grain yield	[Mg ha^{-1}]	2.8 - 4.9	3.9 (1.0)	-	3.0	5.4 - 8.1	6.7 (1.0)	3.3 - 9.2	5.4 (1.9)	4.0 - 9.0	6.8 (2.0)	4.0 - 6.3	4.9 (1.2)

S, surface irrigated; P, pressurized irrigated; L, landrace seed; H, hybrid seed; W, with synthetic fertilizers; S-S, spring-summer; A-W, autumn-winter. [a] Minimum and maximum input rates reported for Mexican states with available data, except for irrigation-related inputs. [b] Simple average and (standard deviation) of reported input rates, except for irrigation-related inputs. [c] Based on estimated diesel use in the mechanical field operations performed. [d] Only for manual field operations. [e] Only for draft animal-powered field operations. [f] Based on N, P_2O_5, and K_2O typical content of applied fertilizers. [g] Range is the minimum and maximum of state-level values; average and (standard deviation) correspond to the national weighted average and standard deviation using planted area in every Mexican state under each irrigated production system as weight; human labor is only for irrigation application; for surface irrigated production systems, electricity and diesel inputs are only for groundwater pumping; for pressurized irrigated systems, electricity and diesel inputs comprise both groundwater pumping and operating of pressurized irrigation systems.

Table A4. Energy use and cumulative exergy consumption (*CExC*) associated with the production of farming inputs.

Farming input	Unit	Energy	Reference	*CExC*	Reference
		[MJ unit^{-1}]		[MJ unit^{-1}]	
Hybrid seed	[kg]	45.3	[3]	52.1	Own estimate[h]
Landrace seed[a]	[kg]	14.7	[4]	16.9	Own estimate[h]
Muriate of potash	[kg]	8.0	[5]	11.5	Own estimate[i]
Potassium nitrate	[kg]	11.0	[5]	12.8	Own estimate[j]
Diammonium phosphate	[kg]	19.0	[5]	23.3	Own estimate[k]
Monoammonium phosphate	[kg]	16.0	[5]	19.9	Own estimate[k]
Ammonia	[kg]	42.0	[5]	48.2	[6]
Ammonium nitrate	[kg]	21.0	[5]	25.1	[7]
Ammonium sulfate	[kg]	11.0	[5]	20.8	Own estimate[l]
Single superphosphate	[kg]	1.7	[8]	15.4	Own estimate[m]
Triple superphosphate	[kg]	9.3	[5]	26.7	[7]
Urea	[kg]	30.0	[5]	33.3	[7]
NPK compound	[kg]	11.6	[9]	15.6	Own estimate[n]
Insecticides	[kg]	38.3[b]	[10]	56.5	Own estimate[o]
	[L]	132.7[b]	[10]	173.9	Own estimate[o]
Herbicides	[kg]	203.9[b]	[10]	371.6	Own estimate[o]
	[L]	90.6[b]	[10]	153.5	Own estimate[o]
Fungicides	[kg]	118.5[b]	[10]	160.0	Own estimate[o]
	[L]	108.2[b]	[10]	120.4	Own estimate[o]
Rodenticides	[kg]	225.8[c]	[10]	291.1	Own estimate[o]
Farm machinery	[kg]	108.0	[11]	118.0[p]	[12]
Diesel	[L]	42.8[d]	[5]	43.9	[13]
Ship bunker fuel	[L]	44.8[e]	[5]	48.6	[6,13]
Jet fuel	[L]	36.3[f]	[5]	39.6	[6,13]
Electricity	[kWh]	9.9	Own estimate[g]	12.5	Own estimate[q]

[a] Also known as *criollo* seed. [b] Average of estimated values for applied insecticides, herbicides, and fungicides products based on energy use for manufacturing, formulation, and packaging from [10]. [c] Estimated as the average energy use for manufacturing, formulation, and packaging for all pesticides from [10]. [d] Net heating value (*NHV*) of 35.7 MJ L^{-1}; approximately 7.1 MJ L^{-1} associated with upstream operations. [e] *NHV* of 40.0 MJ L^{-1}; approximately 5.8 MJ L^{-1} associated with upstream operations. [f] *NHV* of 31.9 MJ L^{-1}; approximately 4.3 MJ L^{-1} associated with upstream operations. [g] Based on annual average generation efficiency and fuel mix for the 2004-2008 period calculated from [14], upstream energy use in fossil fuels processing from [5], and electricity transmission, transformation, and distribution losses assumed to be 6% [15]. [h] Based on energy-to-*CExC* ratio for seed calculated from [12]. [i] Considering sylvite as raw material with a K_2O content of approximately 63% [16], KCl production efficiency of about 85% [17], energy inputs for KCl production from [5], chemical exergy of sylvite (18.5 kJ mol^{-1}) from [18], exergy-to-energy ratios of energy inputs from [6], and cumulative degree of perfection (*CDP*, i.e. useful exergy-to-*CExC* ratio) from [13]. [j] Based on material inputs for NK production from [5] and *CExC* of material inputs from [7]. [k] Based on material and energy inputs for DAP production from [5], *CExC* of material inputs from [6,7], exergy-to-energy ratios of energetic inputs from [6], and corresponding *CDP* from [13]. [l] Based on material inputs for AS production from [5] and *CExC* of material inputs from [6]. [m] Based on material and energy inputs for SSP production from [19], chemical exergy of phosphoric rock (19.4 kJ mol^{-1}) from [6], energy inputs for phosphoric rock beneficiation from [5], production efficiency of 100%, exergy-to-energy ratios of energy inputs from [6], and corresponding *CDP* from [13]. [n] Assuming 17-17-17 and corresponding *CExC* from [20]. [o] Based on *CExC* of insecticides, herbicides and fungicides products (344.0, 368.0, and 256.0 MJ per kg of active ingredient, respectively) from [13]; per-liter figures were calculated using average density (1.1, 1.1, 3.8 kg L^{-1} of product, respectively). [p] Average of reported range. [q] Based on average proportions electricity generated from fossil fuels and hydro-sources in Mexico for the 2000-2008 period according to [21] and *CExC* of 4.2 MJ MJ^{-1} and 6.0×10^{-3} MJ MJ^{-1}, respectively [13].

Table A5. Diesel use in mechanical field operations and embodied energy and greenhouse gas emissions in farm machinery used.

Category	Operation	Diesel	Reference	Machinery	Embodied energy[a]	Embodied GHG emissions[b]		
		[L ha^{-1}]			[MJ ha^{-1}]	[kg-CO_2 ha^{-1}]	[kg-N_2O ha^{-1}]	[kg-CH_4 ha^{-1}]
Land preparation	Bush clearing	10.5	[22]	Tractor + shredder	67.0	6.0	8.0×10^{-5}	7.4×10^{-3}
	Land levelling	10.4	[23]	Tractor + levelling blade	66.4	5.9	7.9×10^{-5}	7.3×10^{-3}
	Land flattening	5.0	[24]	Tractor + land roller	31.9	2.9	3.8×10^{-5}	3.5×10^{-3}
	Plowing	11.9	[25]	Tractor + disk plow	102.0	9.1	1.2×10^{-4}	1.1×10^{-2}
	Subsoiling	14.6	[26]	Tractor + subsoiler	93.1	8.3	1.1×10^{-4}	1.0×10^{-2}
	Harrowing	3.8	[25]	Tractor + disk harrow	55.0	4.9	6.6×10^{-5}	6.1×10^{-3}
	Furrowing	5.6	[22]	Tractor + furrower	20.5	1.8	2.4×10^{-5}	2.3×10^{-3}
Sowing	Sowing	5.7	[25]	Tractor + row crop planter	58.0	5.2	6.9×10^{-5}	6.4×10^{-3}
Fertilization	Solid fertilizer application	5.6	[27]	Tractor + fertilizer spreader	60.0	5.4	7.2×10^{-5}	6.6×10^{-3}
	NH_3 injection	8.0	[3]	Tractor + NH_3 applicator	60.0	5.4	7.2×10^{-5}	6.6×10^{-3}
Weed and pest control	Weeding/cultivation	4.8	[25]	Tractor + field cultivate	42.0	3.8	5.0×10^{-5}	4.6×10^{-3}
	Hoeing	1.9	[27]	Tractor + rotary hoe	10.6	0.9	1.3×10^{-5}	1.2×10^{-3}
	Pesticide application	0.9	[27]	Tractor + sprayer	56.0	5.0	6.7×10^{-5}	6.2×10^{-3}
Cultural operations	Ridging	4.2	[27]	Tractor + hiller	23.9	2.1	2.8×10^{-5}	2.6×10^{-3}
Irrigation and drainage	Field bordering/ditching	5.6	[22]	Tractor + disk plow	20.5	1.8	2.4×10^{-5}	2.3×10^{-3}
Harvesting	Harvesting	15.0	[27]	Combine + head	186.0	16.7	2.2×10^{-4}	2.1×10^{-2}
	Mowing and binding sheaves	10.8	[27]	Tractor + binder	66.0	5.9	7.9×10^{-5}	7.3×10^{-3}

[a] Based on values reported in [26,28]. [b] Based on energy mix for manufacturing, transportation, and repairs of farm machinery as reported in [28].

Table A6. Estimated energy use and cumulative exergy consumption (*CExC*) for transportation and distribution of farming inputs.[a]

Farming input	Per-cent share of imports in total national apparent consumption[d]	Imports transportation[e]		Domestic transportation		Domestic distribution	
		Energy [MJ ton^{-1}]	*CExC*[f] [MJ ton^{-1}]	Energy [MJ ton^{-1}]	*CExC*[f] [MJ ton^{-1}]	Energy [MJ ton^{-1}]	*CExC*[f] [MJ ton^{-1}]
Hybrid seed	7.0	33.1	34.5	418.1	429.7	64.8	66.6
Landrace seed[b]	0.0	-	-	-	-	-	-
Muriate of potash	100.0	254.0	271.8	418.1	429.7	64.8	66.6
Potassium nitrate	100.0	515.4	540.8	418.1	429.7	64.8	66.6
Diammonium phosphate	100.0	97.2	104.9	418.1	429.7	64.8	66.6
Monoammonium phosphate	100.0	207.8	221.9	418.1	429.7	64.8	66.6
Ammonia	0.0	-	-	418.1	429.7	64.8	66.6
Ammonium nitrate	78.5	428.4	463.3	418.1	429.7	64.8	66.6
Ammonium sulfate	4.0	16.1	17.4	418.1	429.7	64.8	66.6
Single superphosphate	0.0	-	-	418.1	429.7	64.8	66.6
Triple superphosphate	0.0	-	-	418.1	429.7	64.8	66.6
Urea	100.0	439.2	476.3	418.1	429.7	64.8	66.6
NPK Compound	100.0	508.5	549.2	418.1	429.7	64.8	66.6
Insecticides[c]	56.1	1,879.9	2,043.4	418.1	429.7	64.8	66.6
Herbicides[c]	57.4	447.1	481.2	418.1	429.7	64.8	66.6
Fungicides[c]	86.6	5,544.3	6,044.0	418.1	429.7	64.8	66.6
Rodenticides	58.7	359.1	382.2	418.1	429.7	64.8	66.6

[a] Only includes fossil fuel consumed in farming input transportation and distribution. [b] Also known as *criollo* seed; farmers save the seed from previous harvests and hence, transportation and distribution are not needed. [c] Per-liter of product values were estimated using typical density (in kg L^{-1}) of each pesticide product. [d] Annual average for the 2004-2008 period. [e] Weighted average according to per-cent share of imports in estimated total national apparent consumption (see section 2.3 in main text for additional details). [f] Based on *CExC* of the fossil fuels consumed.

Table A7. Human labor energy use in manual field operations.

Category	Operation	Human labor energy [MJ h^{-1} of work]	Reference
Land preparation	Land clearing	1.3	[29]
	Land levelling	2.4	[30]
	Bush clearing	1.8	[30]
	Subsoiling	2.4	[30]
Sowing	Sowing	1.6	[29]
Fertilization	Fertilizer application (hand broadcasting)	1.7	[30]
Weed and pest control	Weeding	1.1	[29]
	Hoeing	1.5	[30]
	Pesticide application	1.7	[30]
	Scaring birds	1.5	[29]
Cultural operations	Ridging	1.6	[29]
	Cutting side buds/bending of maize tops	1.3	[29]
Irrigation and drainage	Ditching	1.6	[30]
Harvesting	Cutting heads	0.8	[29]
	Harvesting	0.8	[29]
	Maize cobs packing	1.3	[29]
	Binding sheaves/fodder bundling	1.9	[29]
	Mowing and binding sheaves	3.8	[29]

Table A8. Animal labor energy use in animal-powered field operations.

Category	Operation	Animal labor energy[a] [MJ ha^{-1}]	Reference
Land preparation	Plowing	420.0	[31]
	Harrowing	157.5	[31]
	Furrowing	117.6	[4,32]
Sowing	Sowing	189.0	[31]
Weed and pest control	Weeding/hoeing	100.8	[25]
Cultural labors	Ridging	504.0	[4,32]

[a] Calculated assuming 10.5 MJ h^{-1} of work [26].

Table A9. Greenhouse gas emission factors for the production of farming inputs.

Farming input	Unit	[kg CO_2 unit^{-1}]	[kg N_2O unit^{-1}]	[kg CH_4 unit^{-1}]	Reference
Hybrid seed	[kg]	2.2	2.2×10^{-3}	3.8×10^{-2}	Own estimate[c]
Landrace seed[a]	[kg]	na	na	na	-
Muriate of potash	[kg]	0.6	7.7×10^{-6}	9.0×10^{-4}	[5]
Potassium nitrate	[kg]	0.7	2.2×10^{-3}	1.4×10^{-3}	[5]
Diammonium phosphate	[kg]	1.2	1.5×10^{-5}	2.5×10^{-3}	[5]
Monoammonium phosphate	[kg]	1.0	1.5×10^{-5}	2.0×10^{-3}	[5]
Ammonia	[kg]	2.3	1.5×10^{-5}	6.6×10^{-3}	[5]
Ammonium nitrate	[kg]	1.2	3.8×10^{-3}	3.2×10^{-3}	[5]
Ammonium sulfate	[kg]	0.6	5.0×10^{-6}	1.7×10^{-3}	[5]
Single superphosphate	[kg]	0.2	7.8×10^{-6}	6.0×10^{-4}	[33]
Triple superphosphate	[kg]	0.6	1.1×10^{-5}	1.1×10^{-3}	[5]
Urea	[kg]	1.0	1.6×10^{-5}	4.8×10^{-3}	[5]
NPK compound	[kg]	0.6	1.8×10^{-3}	6.2×10^{-4}	[33]
Insecticides	[kg]	2.6	3.3×10^{-5}	3.5×10^{-3}	Own estimate[d]
	[L]	8.8	1.1×10^{-4}	1.2×10^{-2}	Own estimate[d]
Herbicides	[kg]	13.6	1.6×10^{-4}	1.8×10^{-2}	Own estimate[d]
	[L]	6.0	7.1×10^{-5}	8.1×10^{-3}	Own estimate[d]
Fungicides	[kg]	7.9	9.3×10^{-5}	1.1×10^{-2}	Own estimate[d]
	[L]	7.2	8.5×10^{-5}	9.7×10^{-3}	Own estimate[d]
Rodenticides	[kg]	15.0	1.8×10^{-4}	2.0×10^{-2}	Own estimate[d]
Farm machinery	[GJ][b]	89.6	1.2×10^{-3}	1.1×10^{-1}	Own estimate[e]
Diesel	[L]	3.0	1.0×10^{-3}	2.6×10^{-3}	[5,34][f]
Ship bunker fuel	[L]	3.5	2.9×10^{-5}	2.5×10^{-3}	[5,34][f]
Jet fuel	[L]	2.6	6.8×10^{-5}	1.9×10^{-3}	[5,34][f]
Electricity	[kWh]	0.6	4.4×10^{-6}	8.8×10^{-4}	Own estimate[g]

na, Not available. [a] Also known as *criollo* seed. [b] Per GJ of manufacturing energy use. [c] Based on total GHG emissions (3.8 kg CO_2e kg^{-1} seed) from [3], fuel mix for seed production from [28], and default emission factors from [34]. [d] Based on total GHG emissions per unit of manufacturing energy use (6.9×10^{-2} kg CO_2e MJ^{-1}) from [35] and $CO_2 : N_2O : CH_4$ split for generic herbicide and insecticide products from [5]. [e] Based on fuel mix for machinery manufacturing, transportation and repairs from [28] and default emission factors from [34]; GHG emissions associated with manufacturing irrigation equipment from [2]. [f] Comprises both emissions from upstream processing of fuel and on-site emissions from fuel consumption. [g] GHG emissions from fossil fuel consumption in electricity generation estimated based on average energy mix for the 2004-2008 period calculated from [14] and emission factors comprising both upstream processing of fuels [5] and on-site fuel consumption [34,36].

Table A10. Estimated greenhouse gas emission factors for farming input transportation and distribution.

Farming input	Per-cent share of imports in total National Apparent Consumption[c]	Imports transportation[d]			Domestic transportation			Domestic distribution		
		[kg CO_2 ton^{-1}]	[kg N_2O ton^{-1}]	[kg CH_4 ton^{-1}]	[kg CO_2 ton^{-1}]	[kg N_2O ton^{-1}]	[kg CH_4 ton^{-1}]	[kg CO_2 ton^{-1}]	[kg N_2O ton^{-1}]	[kg CH_4 ton^{-1}]
Hybrid maize seed	7.0	1.8	1.6×10^{-5}	1.4×10^{-3}	29.7	2.7×10^{-4}	2.5×10^{-2}	4.6	4.2×10^{-5}	3.8×10^{-3}
Landrace seed[a]	0.0	-	-	-	-	-	-	-	-	-
Muriate of potash	100.0	19.0	1.7×10^{-4}	1.4×10^{-2}	29.7	2.7×10^{-4}	2.5×10^{-2}	4.6	4.2×10^{-5}	3.8×10^{-3}
Potassium nitrate	100.0	37.9	3.4×10^{-4}	3.0×10^{-2}	29.7	2.7×10^{-4}	2.5×10^{-2}	4.6	4.2×10^{-5}	3.8×10^{-3}
Diammonium phosphate	100.0	7.3	6.3×10^{-5}	5.4×10^{-3}	29.7	2.7×10^{-4}	2.5×10^{-2}	4.6	4.2×10^{-5}	3.8×10^{-3}
Monoammonium phosphate	100.0	15.5	1.4×10^{-4}	1.2×10^{-2}	29.7	2.7×10^{-4}	2.5×10^{-2}	4.6	4.2×10^{-5}	3.8×10^{-3}
Ammonia	0.0	-	-	-	29.7	2.7×10^{-4}	2.5×10^{-2}	4.6	4.2×10^{-5}	3.8×10^{-3}
Ammonium nitrate	78.5	32.4	2.8×10^{-4}	2.4×10^{-2}	29.7	2.7×10^{-4}	2.5×10^{-2}	4.6	4.2×10^{-5}	3.8×10^{-3}
Ammonium sulfate	4.0	1.2	1.0×10^{-5}	8.9×10^{-4}	29.7	2.7×10^{-4}	2.5×10^{-2}	4.6	4.2×10^{-5}	3.8×10^{-3}
Single superphosphate	0.0	-	-	-	29.7	2.7×10^{-4}	2.5×10^{-2}	4.6	4.2×10^{-5}	3.8×10^{-3}
Triple superphosphate	0.0	-	-	-	29.7	2.7×10^{-4}	2.5×10^{-2}	4.6	4.2×10^{-5}	3.8×10^{-3}
Urea	100.0	33.3	2.9×10^{-4}	2.4×10^{-2}	29.7	2.7×10^{-4}	2.5×10^{-2}	4.6	4.2×10^{-5}	3.8×10^{-3}
NPK Compound	100.0	38.4	3.3×10^{-4}	2.8×10^{-2}	29.7	2.7×10^{-4}	2.5×10^{-2}	4.6	4.2×10^{-5}	3.8×10^{-3}
Insecticides[b]	56.1	133.3	3.2×10^{-3}	1.0×10^{-1}	28.8	2.6×10^{-4}	2.4×10^{-2}	4.6	4.2×10^{-5}	3.8×10^{-3}
Herbicides[b]	57.4	32.4	5.5×10^{-4}	2.5×10^{-2}	28.8	2.6×10^{-4}	2.4×10^{-2}	4.6	4.2×10^{-5}	3.8×10^{-3}
Fungicides[b]	86.6	391.7	10.0×10^{-3}	3.0×10^{-1}	28.8	2.6×10^{-4}	2.4×10^{-2}	4.6	4.2×10^{-5}	3.8×10^{-3}
Rodenticides	58.7	26.1	3.8×10^{-4}	2.0×10^{-2}	28.8	2.6×10^{-4}	2.4×10^{-2}	4.6	4.2×10^{-5}	3.8×10^{-3}

[a] Also known as *criollo* seed; farmers save the seed from previous harvests and hence, transportation and distribution are not needed. [b] Per-liter of product values were estimated using typical density (in kg L^{-1}) of each pesticide product. [c] Annual average for the 2004-2008 period. [d] Weighted according to per-cent share of imports in estimated total National Apparent Consumption (see section 2.5 in main text for further details).

Table A11. Estimated per-hectare total energy use, energy intensity (*EI*), net energy (*NE*), and energy output-input ratio (*ER*) for the selected maize production systems in the Mexican states with data available from [1].

Production system[a]	Growing season[b]	Mexican State	Grain yield[c] [kg ha^{-1}]	Total energy use[d] [MJ ha^{-1}]	*EI* [MJ kg^{-1} grain]	*NE* [MJ ha^{-1}]	*ER*
RLWO	S-S	Nuevo León	1,000.0	1,770.0	1.8	11,960.0	7.8
		Guanajuato	2,440.0	1,870.0	0.8	31,620.0	17.9
		San Luis Potosí	1,500.0	2,060.0	1.4	18,530.0	10.0
		Guerrero	2,750.0	1,380.0	0.5	36,360.0	27.3
		Oaxaca	1,080.0	3,700.0	3.4	11,120.0	4.0
		Tabasco	1,250.0	3,310.0	2.6	13,840.0	5.2
RHWO	S-S	Aguascalientes	1,500.0	3,020.0	2.0	17,560.0	6.8
		Oaxaca	1,500.0	4,320.0	2.9	16,260.0	4.8
		Tabasco	1,380.0	3,900.0	2.8	15,040.0	4.8
RLW	S-S	Chihuahua	1,500.0	5,830.0	3.9	14,760.0	3.5
		Guanajuato	2,800.0	5,910.0	2.1	32,520.0	6.5
		Michoacán	2,410.0	14,890.0	6.2	18,180.0	2.2
		México	2,800.0	7,590.0	2.7	30,840.0	5.1
		Guerrero	2,670.0	6,610.0	2.5	30,030.0	5.5
		Tlaxcala	2,400.0	11,270.0	4.7	21,670.0	2.9
		Oaxaca	1,650.0	8,760.0	5.3	13,890.0	2.6
		Veracruz	2,100.0	13,730.0	6.5	15,090.0	2.1
RHW	S-S	Chihuahua	1,500.0	7,920.0	5.3	12,670.0	2.6
		Durango	950.0	4,510.0	4.7	8,530.0	2.9
		Aguascalientes	2,500.0	5,970.0	2.4	28,340.0	5.7
		Guanajuato	4,500.0	9,940.0	2.2	51,820.0	6.2
		Jalisco	5,000.0	18,280.0	3.7	50,350.0	3.7
		Michoacán	2,590.0	14,800.0	5.7	20,750.0	2.4
		México	2,500.0	10,460.0	4.2	23,850.0	3.3
		Guerrero	3,700.0	10,110.0	2.7	40,670.0	5.0
		Morelos	3,600.0	26,600.0	7.4	22,810.0	1.9
		Tlaxcala	2,700.0	12,040.0	4.5	25,020.0	3.1
		Chiapas	2,400.0	5,130.0	2.1	27,810.0	6.4
		Oaxaca	3,000.0	8,010.0	2.7	33,170.0	5.1
		Tabasco	1,820.0	9,960.0	5.5	15,020.0	2.5
		Yucatán	3,000.0	6,740.0	2.2	34,430.0	6.1
SLW	S-S	Nuevo León	4,000.0	3,770.0	0.9	51,130.0	14.5
		Michoacán	4,850.0	20,760.0	4.3	45,800.0	3.2
		Guerrero	2,800.0	8,710.0	3.1	29,720.0	4.4
	A-W	Guerrero	3,000.0	9,010.0	3.0	32,160.0	4.6
SHW	S-S	Sinaloa	7,000.0	14,030.0	2.0	82,050.0	6.8
		Chihuahua	8,080.0	48,570.0	6.0	62,320.0	2.3
		Durango	6,760.0	10,350.0	1.5	82,440.0	9.0
		Aguascalientes	5,780.0	35,360.0	6.1	43,970.0	2.2
		Guanajuato	8,000.0	17,390.0	2.2	92,410.0	6.3
		Jalisco	7,000.0	19,880.0	2.8	76,200.0	4.8
		Michoacán	5,380.0	21,570.0	4.0	52,270.0	3.4
		Guerrero	5,750.0	21,190.0	3.7	57,730.0	3.7
	A-W	Sonora	6,300.0	23,600.0	3.7	62,870.0	3.7
		Sinaloa	9,150.0	18,840.0	2.1	106,750.0	6.7
		Nuevo León	4,200.0	13,330.0	3.2	44,310.0	4.3
		Tamaulipas	5,000.0	10,830.0	2.2	57,790.0	6.3
		Colima	5,000.0	16,770.0	3.3	51,860.0	4.1
		Michoacán	3,330.0	42,270.0	12.7	3,440.0	1.1
		Guerrero	4,500.0	13,960.0	3.1	47,810.0	4.4
PHW	S-S	Chihuahua	8,500.0	63,570.0	7.5	53,090.0	1.8
		Nuevo León	8,000.0	32,950.0	4.1	76,850.0	3.3
		Aguascalientes	5,780.0	43,960.0	7.6	35,370.0	1.8
		Guanajuato	9,000.0	37,570.0	4.2	86,000.0	3.3
		Michoacán	5,380.0	32,590.0	6.1	41,250.0	2.3
		Tlaxcala	4,000.0	22,750.0	5.7	32,150.0	2.4
	A-W	Baja California Sur	6,280.0	45,940.0	7.3	40,250.0	1.9
		Tamaulipas	4,500.0	22,750.0	5.0	39,020.0	2.7
		Guerrero	4,000.0	22,570.0	5.6	32,330.0	2.4

[a] R, rain-fed; S, surface irrigated; P, pressurized irrigated, L, landrace seed; H, hybrid seed; WO, without synthetic fertilizers; W, with synthetic fertilizers. [b] S-S, spring-summer; A-W, autumn-winter. [c] As reported in [1]. [d] In the case of irrigated production systems, total energy use was calculated using state-level irrigation energy data from [2].

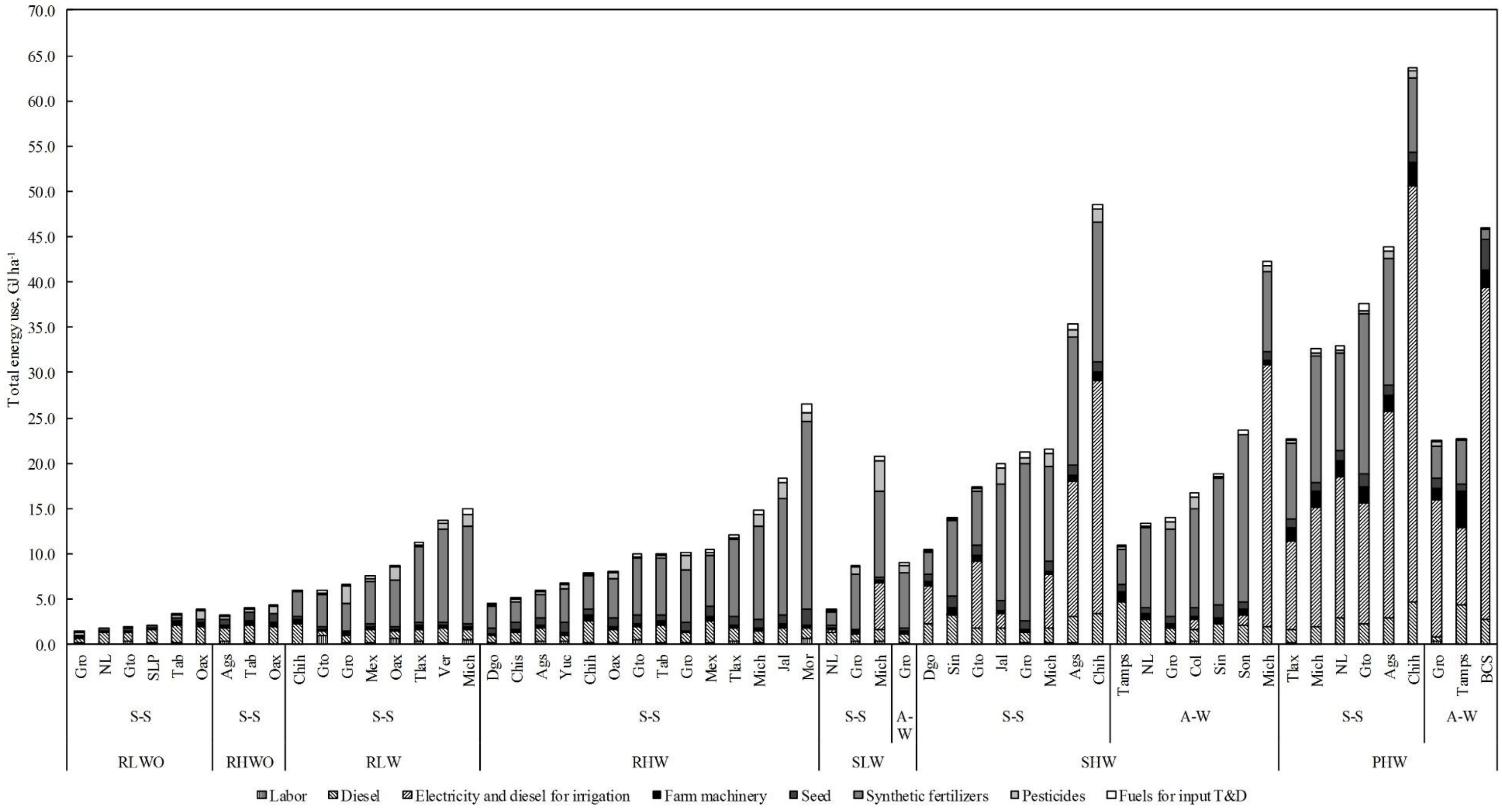

Figure A1. Estimated per-hectare total energy use for the selected maize production systems in the Mexican states with data available from [1]. S-S, spring-summer growing season; A-W, autumn-winter growing season; R, rain-fed; S, surface irrigated; P, pressurized irrigated; L, landrace seed; H, hybrid seed; W, with synthetic fertilizers; WO, without synthetic fertilizers; T&D, transportation and distribution. Labor comprises both human labor and animal labor. Farm machinery includes irrigation equipment. Bars with line patterns represent direct energy inputs. Bars with solid colors represent indirect energy inputs.

Table A12. Standard deviation of estimated per-hectare total energy use, energy intensity (*EI*), net energy (*NE*), and energy output-input ratio (*ER*) for the maize production systems.

Production system[a]	Growing season[b]	Total energy use [GJ ha^{-1}]	*EI* [GJ Mg^{-1} grain]	*NE* [GJ ha^{-1}]	*ER*
RLWO	S-S	0.93	1.12	10.81	8.96
RHWO	S-S	0.66	0.49	1.26	1.16
RLW	S-S	3.56	1.71	7.87	1.67
RHW	S-S	5.90	1.64	12.96	1.63
SLW[c]	S-S	6.16	1.44	12.39	2.29
	A-W[d]	-	-	-	-
SHW[c]	S-S	5.78	1.04	16.04	2.50
	A-W	3.95	0.75	23.77	1.16
PHW[c]	S-S	3.78	1.71	25.57	0.61
	A-W	2.47	1.84	16.55	0.42

[a] R, rain-fed; S, surface irrigated; P, pressurized irrigated, L, landrace seed; H, hybrid seed; WO, without synthetic fertilizers; W, with synthetic fertilizers. [b] S-S, spring-summer; A-W, autumn-winter. [c] For irrigated maize production systems, the standard deviation was computed using the national weighted averages (by planted area) of irrigation energy inputs instead of the state-level values. [d] Data were available only for one Mexican state.

Table A13. Estimated per-hectare cumulative exergy consumption (*CExC*), exergy intensity (*ExI*), net exergy (*NEx*), and exergy output-input ratio (*ExR*) for the selected maize production systems in the Mexican states with data available from [1].

Production system[a]	Growing season[b]	Mexican State	*CExC*[c] [MJ ha^{-1}]	*ExI* [MJ kg^{-1} grain]	*NEx* [MJ ha^{-1}]	*ExR*
RLWO	S-S	Nuevo León	1,780.0	1.8	14,490.0	9.1
		Guanajuato	1,760.0	0.7	37,960.0	22.6
		San Luis Potosí	1,910.0	1.3	22,500.0	12.8
		Guerrero	1,490.0	0.5	43,270.0	30.1
		Oaxaca	4,170.0	3.9	13,400.0	4.2
		Tabasco	3,630.0	2.9	16,720.0	5.6
RHWO	S-S	Aguascalientes	3,140.0	2.1	21,270.0	7.8
		Oaxaca	4,890.0	3.3	19,530.0	5.0
		Tabasco	4,340.0	3.1	18,120.0	5.2
RLW	S-S	Chihuahua	6,340.0	4.2	18,070.0	3.8
		Guanajuato	10,830.0	3.9	34,740.0	4.2
		Michoacán	19,570.0	8.1	19,650.0	2.0
		México	9,370.0	3.3	36,200.0	4.9
		Guerrero	8,770.0	3.3	34,690.0	5.0
		Tlaxcala	13,910.0	5.8	25,150.0	2.8
		Oaxaca	10,280.0	6.2	16,580.0	2.6
		Veracruz	15,800.0	7.5	18,380.0	2.2
RHW	S-S	Chihuahua	8,900.0	5.9	15,510.0	2.7
		Durango	5,160.0	5.4	10,300.0	3.0
		Aguascalientes	10,800.0	4.3	29,890.0	3.8
		Guanajuato	12,710.0	2.8	60,530.0	5.8
		Jalisco	21,840.0	4.4	59,530.0	3.7
		Michoacán	18,980.0	7.3	23,170.0	2.2
		México	13,530.0	5.4	27,160.0	3.0
		Guerrero	14,140.0	3.8	46,080.0	4.3
		Morelos	30,240.0	8.4	28,350.0	1.9
		Tlaxcala	14,750.0	5.5	29,200.0	3.0
		Chiapas	8,490.0	3.5	30,570.0	4.6
		Oaxaca	9,990.0	3.3	38,840.0	4.9
		Tabasco	11,670.0	6.4	17,950.0	2.5
		Yucatán	7,910.0	2.6	40,910.0	6.2
SLW	S-S	Nuevo León	4,300.0	1.1	60,800.0	15.1
		Michoacán	24,930.0	5.1	54,000.0	3.2
		Guerrero	11,820.0	4.2	33,750.0	3.8
SLW	A-W	Guerrero	12,400.0	4.1	36,420.0	3.9
SHW	S-S	Sinaloa	15,620.0	2.2	98,300.0	7.3
		Chihuahua	57,990.0	7.2	73,520.0	2.3
		Durango	12,190.0	1.8	97,830.0	9.0
		Aguascalientes	41,440.0	7.2	52,630.0	2.3
		Guanajuato	20,270.0	2.5	109,930.0	6.4
		Jalisco	23,840.0	3.4	90,080.0	4.8
		Michoacán	26,790.0	5.0	60,770.0	3.3
		Guerrero	26,610.0	4.6	66,970.0	3.5
SHW	A-W	Sonora	26,630.0	4.2	75,900.0	3.8
		Sinaloa	21,820.0	2.4	127,100.0	6.8
		Nuevo León	15,090.0	3.6	53,260.0	4.5
		Tamaulipas	13,210.0	2.6	68,170.0	6.2
		Colima	26,580.0	5.3	54,800.0	3.1
		Michoacán	53,470.0	16.1	730.0	1.0
		Guerrero	19,660.0	4.4	53,580.0	3.7
PHW	S-S	Chihuahua	80,000.0	9.4	58,340.0	1.7
		Nuevo León	44,300.0	5.5	85,900.0	2.9
		Aguascalientes	53,000.0	9.2	41,070.0	1.8
		Guanajuato	53,900.0	6.0	92,580.0	2.7
		Michoacán	42,540.0	7.9	45,020.0	2.1
		Tlaxcala	29,070.0	7.3	36,030.0	2.2
PHW	A-W	Baja California Sur	57,660.0	9.2	44,550.0	1.8
		Tamaulipas	26,910.0	6.0	46,330.0	2.7
		Guerrero	30,400.0	7.6	34,700.0	2.1

[a] R, rain-fed; S, surface irrigated; P, pressurized irrigated, L, landrace seed; H, hybrid seed; WO, without synthetic fertilizers; W, with synthetic fertilizers. [b] S-S, spring-summer; A-W, autumn-winter. [c] In the case of irrigated production systems, *CExC* was calculated using state-level irrigation energy data from [2].

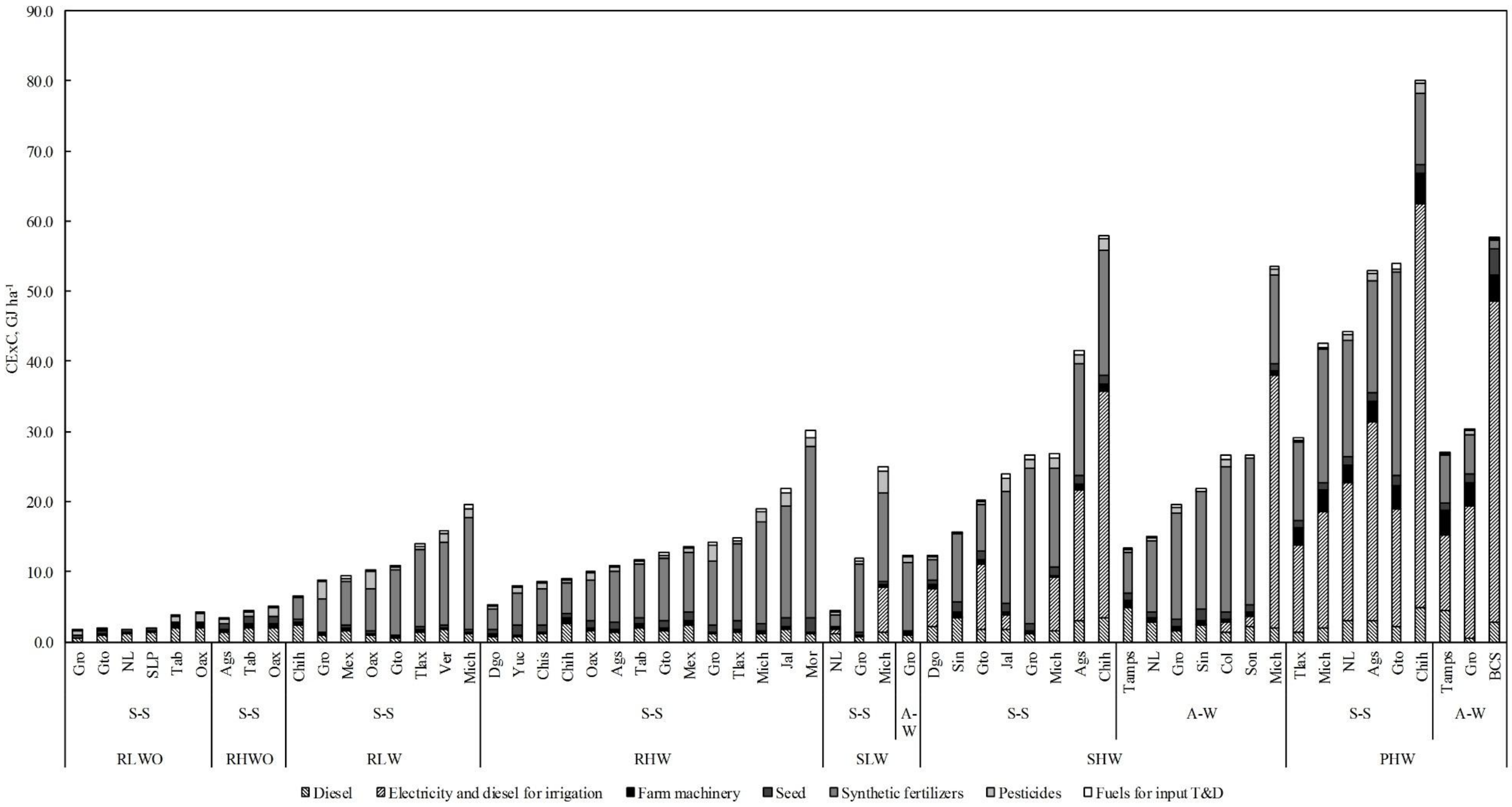

Figure A2. Estimated per-hectare cumulative exergy consumption (*CExC*) for the selected maize production systems in the Mexican states with data available from [1]. S-S, spring-summer growing season; A-W, autumn-winter growing season; R, rain-fed; S, surface irrigated; P, pressurized irrigated; L, landrace seed; H, hybrid seed; W, with synthetic fertilizers; WO, without synthetic fertilizers; T&D, transportation and distribution. Farm machinery includes irrigation equipment. Bars with line patterns represent direct exergetic inputs. Bars with solid colors represent indirect exergetic inputs.

Table A14. Standard deviation of estimated per-hectare cumulative exergy consumption (*CExC*), exergy intensity (*ExI*), net exergy (*NEx*), and exergy output-input ratio (*ExR*) for the maize production systems.

Production system[a]	Growing season[b]	*CExC* [GJ ha^{-1}]	*ExI* [GJ Mg^{-1} grain]	*NEx* [GJ ha^{-1}]	*ExR*
RLWO	S-S	1.14	1.30	12.81	10.25
RHWO	S-S	0.89	0.64	1.58	1.56
RLW	S-S	4.29	1.89	8.49	1.19
RHW	S-S	6.52	1.71	15.08	1.30
SLW[c]	S-S	7.37	1.96	15.62	2.36
	A-W[d]	-	-	-	-
SHW[c]	S-S	7.01	1.30	19.59	2.62
	A-W	4.71	1.14	29.19	1.34
PHW[c]	S-S	6.57	2.04	28.78	0.53
	A-W	2.85	2.45	20.27	0.42

[a] R, rain-fed; S, surface irrigated; P, pressurized irrigated, L, landrace seed; H, hybrid seed; WO, without synthetic fertilizers; W, with synthetic fertilizers. [b] S-S, spring-summer; A-W, autumn-winter. [c] For irrigated maize production systems, the standard deviation was computed using the national weighted averages (by planted area) of irrigation energy inputs instead of the state-level values. [d] Data were available only for one Mexican state.

Table A15. Estimated per-hectare total greenhouse gas (GHG) emissions, GHG emissions intensity (*GHGI*), and GHG emissions per unit energy input ($GHGE_i$) for the selected maize production systems in the Mexican states with data available from [1].

Production system[a]	Growing season[b]	Mexican State	GHG emissions[c] [kg CO$_2$e ha^{-1}]	*GHGI* [kg CO$_2$e kg^{-1} grain]	$GHGE_i$ [kg CO$_2$e MJ^{-1}]
RLWO	S-S	Nuevo León	113.9	113.9×10^{-3}	64.6×10^{-3}
		Guanajuato	107.2	43.9×10^{-3}	57.4×10^{-3}
		San Luis Potosí	130.5	87.0×10^{-3}	63.4×10^{-3}
		Guerrero	72.5	26.4×10^{-3}	52.4×10^{-3}
		Oaxaca	264.4	244.8×10^{-3}	71.5×10^{-3}
		Tabasco	228.9	183.1×10^{-3}	69.1×10^{-3}
RHWO	S-S	Aguascalientes	213.2	142.2×10^{-3}	70.5×10^{-3}
		Oaxaca	341.2	227.5×10^{-3}	78.9×10^{-3}
		Tabasco	305.6	221.5×10^{-3}	78.3×10^{-3}
RLW	S-S	Chihuahua	554.0	369.4×10^{-3}	95.1×10^{-3}
		Guanajuato	625.0	223.2×10^{-3}	105.8×10^{-3}
		Michoacán	1,589.3	659.5×10^{-3}	106.7×10^{-3}
		México	979.0	349.6×10^{-3}	129.0×10^{-3}
		Guerrero	626.9	234.8×10^{-3}	94.8×10^{-3}
		Tlaxcala	1,255.5	523.1×10^{-3}	111.4×10^{-3}
		Oaxaca	866.1	524.9×10^{-3}	98.9×10^{-3}
		Veracruz	1,549.7	738.0×10^{-3}	112.8×10^{-3}
RHW	S-S	Chihuahua	781.8	521.2×10^{-3}	98.7×10^{-3}
		Durango	457.3	481.4×10^{-3}	101.5×10^{-3}
		Aguascalientes	626.4	250.6×10^{-3}	105.0×10^{-3}
		Guanajuato	1,104.2	245.4×10^{-3}	111.0×10^{-3}
		Jalisco	2,093.7	418.7×10^{-3}	114.5×10^{-3}
		Michoacán	1,337.1	516.2×10^{-3}	90.4×10^{-3}
		México	1,079.6	431.8×10^{-3}	103.2×10^{-3}
		Guerrero	1,070.8	289.4×10^{-3}	105.9×10^{-3}
		Morelos	3,398.1	943.9×10^{-3}	127.8×10^{-3}
		Tlaxcala	1,343.8	497.7×10^{-3}	111.6×10^{-3}
		Chiapas	377.8	157.4×10^{-3}	73.6×10^{-3}
		Oaxaca	858.0	286.0×10^{-3}	107.2×10^{-3}
		Tabasco	1,080.9	593.9×10^{-3}	108.5×10^{-3}
		Yucatán	631.5	210.5×10^{-3}	93.7×10^{-3}
SLW	S-S	Nuevo León	353.3	88.3×10^{-3}	93.7×10^{-3}
		Guerrero	962.7	343.8×10^{-3}	110.5×10^{-3}
		Michoacán	1,985.0	409.3×10^{-3}	95.6×10^{-3}
	A-W	Guerrero	997.7	332.6×10^{-3}	110.7×10^{-3}
SHW	S-S	Durango	870.5	128.8×10^{-3}	84.1×10^{-3}
		Sinaloa	1,732.4	247.5×10^{-3}	123.5×10^{-3}
		Guanajuato	1,612.6	201.6×10^{-3}	92.7×10^{-3}
		Jalisco	2,197.4	313.9×10^{-3}	110.5×10^{-3}
		Guerrero	2,569.2	446.8×10^{-3}	121.2×10^{-3}
		Michoacán	2,157.7	401.1×10^{-3}	100.0×10^{-3}
		Aguascalientes	3,345.9	578.9×10^{-3}	94.6×10^{-3}
		Chihuahua	4,382.2	542.4×10^{-3}	90.2×10^{-3}
	A-W	Tamaulipas	1,089.5	217.9×10^{-3}	100.6×10^{-3}
		Nuevo León	1,485.9	353.8×10^{-3}	111.5×10^{-3}
		Guerrero	1,577.4	350.5×10^{-3}	113.0×10^{-3}
		Colima	2,087.9	417.6×10^{-3}	124.5×10^{-3}
		Sinaloa	2,429.6	265.5×10^{-3}	129.0×10^{-3}
		Sonora	2,931.7	465.3×10^{-3}	124.2×10^{-3}
		Michoacán	3,649.4	$1{,}095.9 \times 10^{-3}$	86.3×10^{-3}
PHW	S-S	Tlaxcala	2,032.8	508.2×10^{-3}	89.4×10^{-3}
		Michoacán	3,020.1	561.4×10^{-3}	92.7×10^{-3}
		Nuevo León	2,973.7	371.7×10^{-3}	90.2×10^{-3}
		Guanajuato	3,763.9	418.2×10^{-3}	100.2×10^{-3}
		Aguascalientes	3,891.5	673.3×10^{-3}	88.5×10^{-3}
		Chihuahua	4,709.1	554.0×10^{-3}	74.1×10^{-3}
	A-W	Tamaulipas	1,709.4	379.9×10^{-3}	75.1×10^{-3}
		Guerrero	1,718.0	429.5×10^{-3}	76.1×10^{-3}
		Baja California Sur	3,161.5	503.4×10^{-3}	68.8×10^{-3}

[a] R, rain-fed; S, surface irrigated; P, pressurized irrigated; L, landrace seed; H, hybrid seed; WO, without synthetic fertilizers; W, with synthetic fertilizers. [b] S-S, spring-summer; A-W, autumn-winter. [c] In the case of irrigated production systems, total GHG emissions were calculated using state-level irrigation energy-related GHG emissions from [2].

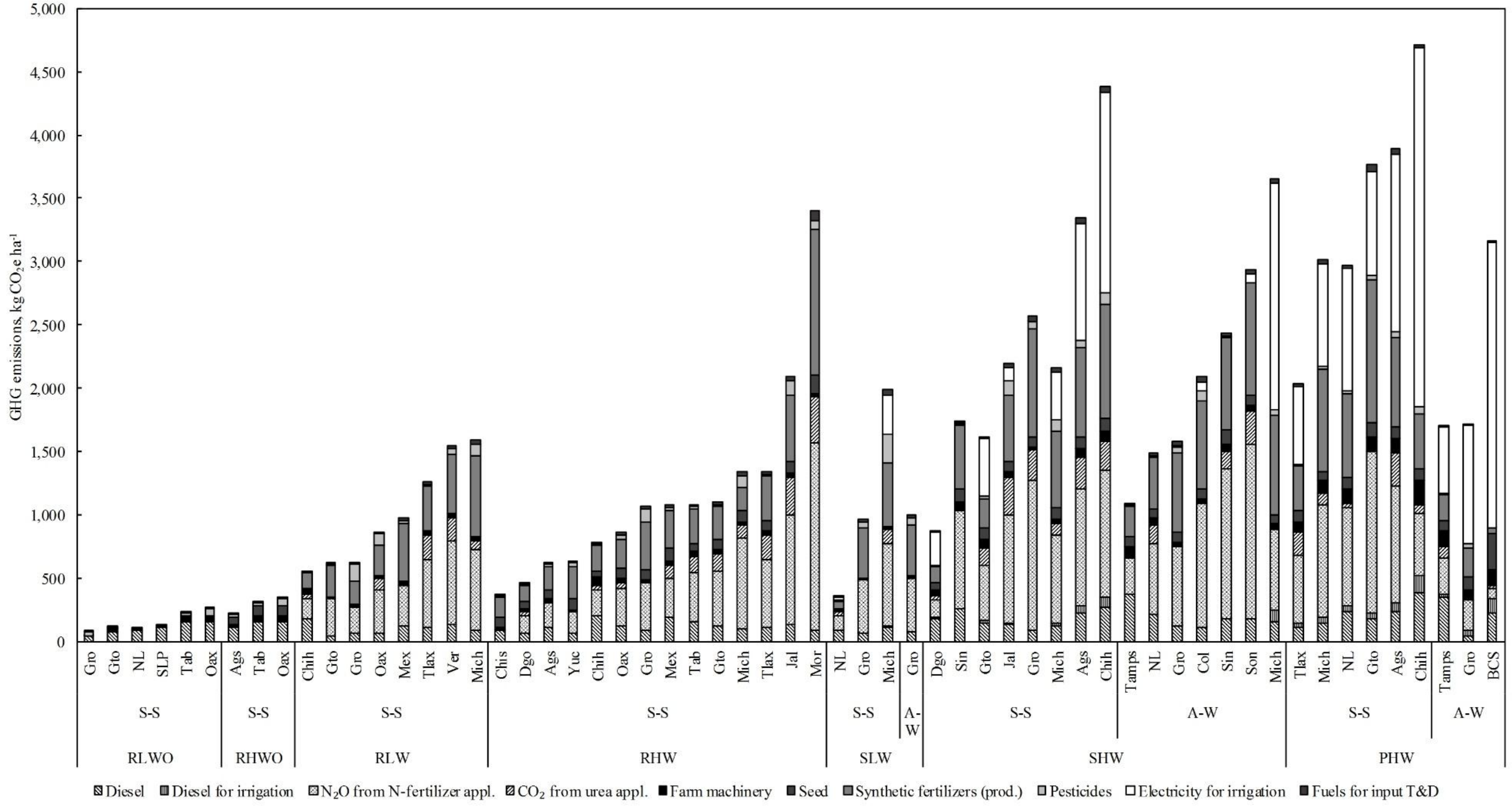

Figure A3. Estimated per-hectare total greenhouse gas (GHG) emissions for the selected maize production systems in the Mexican states with data available from [1]. S-S, spring-summer growing season; A-W, autumn-winter growing season; R, rain-fed; S, surface irrigated; P, pressurized irrigated; L, landrace seed; H, hybrid seed; W, with synthetic fertilizers; WO, without synthetic fertilizers; T&D, transportation and distribution. Farm machinery includes irrigation equipment. Bars with line patterns represent direct emission sources. Bars with solid colors represent indirect emission sources.

Table A16. Standard deviation of estimated per-hectare total greenhouse gas (GHG) emissions, GHG emission intensity (*GHGI*), and GHG emissions per unit input energy (*GHGE*$_i$) for the maize production systems.

Production system[a]	Growing season[b]	Total GHG emissions [kg-CO$_2$e ha^{-1}]	*GHGI* [kg-CO$_2$e Mg^{-1} grain]	*GHGE*$_i$ [kg-CO$_2$e GJ^{-1}]
RLWO	S-S	75.87	83.87	7.15
RHWO	S-S	66.04	47.61	4.69
RLW	S-S	416.02	189.74	11.30
RHW	S-S	778.25	204.02	12.62
SLW[c]	S-S	662.83	156.91	9.91
	A-W[d]	-	-	-
SHW[c]	S-S	724.94	126.15	9.03
	A-W	600.79	109.58	11.69
PHW[c]	S-S	528.93	142.66	5.35
	A-W	247.96	143.49	2.08

[a] R, rain-fed; S, surface irrigated; P, pressurized irrigated, L, landrace seed; H, hybrid seed; WO, without synthetic fertilizers; W, with synthetic fertilizers. [b] S-S, spring-summer; A-W, autumn-winter. [c] For irrigated maize production systems, the standard deviation was computed using the national weighted averages (by planted area) of irrigation energy-related GHG emissions instead of the state-level values. [d] Data were available only for one Mexican state.

Table A17. Estimated planted area (in ha) by maize production system and Mexican state for the spring-summer growing season based on data from [37].

	Production system[a]													
Mexican state	RLWO	RHWO	RLW	RHW	SLWO	SHWO	SLW	SHW	PLWO	PHWO	PLW	PHW	Other[b]	State total
Aguascalientes	29,105.5	1,998.7	10,990.5	2,976.8	1,266.7	323.6	2,390.9	3,380.0	667.0	255.3	730.7	3,451.2	800.2	58,337.2
Baja California	158.8	24.3	9.1	47.4	37.9	9.2	86.5	22.8	120.0	-	44.7	201.2	2.0	763.9
Baja California Sur	917.9	35.3	54.3	46.4	483.6	5.4	93.1	68.0	348.3	24.3	821.6	2,444.3	124.0	5,466.5
Campeche	90,480.6	2,465.4	9,811.1	57,064.1	84.7	7.1	71.1	150.0	83.1	6.5	102.9	346.2	11.6	160,684.5
Coahuila	20,505.4	782.1	136.3	83.1	1,568.7	272.7	94.5	482.1	185.0	96.0	26.4	695.8	2.8	24,930.9
Colima	7,035.7	195.3	6,456.3	3,134.9	212.2	14.2	535.4	448.6	125.4	65.1	194.9	102.6	113.7	18,634.2
Chiapas	394,857.9	1,662.6	45,722.3	47,839.3	1,938.7	5.4	1,962.8	1,898.0	469.7	0.5	160.6	285.9	50.4	496,854.1
Chihuahua	97,034.0	1,637.4	71,571.0	7,982.2	3,092.2	207.5	3,319.8	8,095.9	1,338.3	92.8	6,339.9	13,862.6	1,540.3	216,113.9
Distrito Federal	2,193.0	86.3	1,009.4	95.4	6.8	0.3	2.5	-	20.1	-	4.6	3.4	20.0	3,441.7
Durango	61,751.5	2,277.0	20,520.9	9,758.2	3,096.7	422.5	4,936.6	7,577.4	374.4	37.3	311.0	2,281.5	993.7	114,338.6
Guanajuato	65,475.0	3,199.3	72,472.7	40,787.9	2,999.5	435.7	6,369.8	34,105.4	2,183.4	409.0	2,840.5	17,741.5	5,386.0	254,405.7
Guerrero	233,742.9	1,418.0	78,203.5	57,438.4	2,252.1	39.3	2,415.8	3,163.0	1,860.2	22.3	552.0	361.7	157.3	381,626.4
Hidalgo	102,964.3	2,033.5	28,742.6	3,037.6	10,579.2	6,243.1	4,925.1	10,925.3	745.9	275.4	601.8	301.2	853.6	172,228.6
Jalisco	125,323.7	5,413.5	118,419.1	234,941.7	2,320.5	380.2	5,021.8	17,490.2	1,670.5	266.5	4,002.3	10,048.2	2,535.6	527,833.6
México	106,669.5	2,857.9	198,359.3	14,770.0	9,243.9	748.7	48,771.3	4,768.1	244.3	13.6	1,004.5	164.5	485.6	388,101.2
Michoacán	182,285.5	2,247.8	135,962.7	39,449.4	7,097.0	358.3	20,983.6	27,900.9	501.3	78.8	1,429.0	3,096.0	3,134.9	424,525.1
Morelos	2,635.1	196.2	8,474.2	5,713.7	290.4	34.2	877.8	1,313.1	68.1	0.7	63.6	121.2	105.4	19,893.8
Nayarit	28,059.2	305.5	15,431.8	13,608.5	173.8	20.1	234.3	1,171.8	306.4	87.6	650.0	586.5	167.6	60,802.9
Nuevo León	73,405.9	1,762.2	1,675.5	202.0	2,768.0	179.3	137.6	37.3	831.8	68.7	118.3	272.9	224.0	81,683.6
Oaxaca	285,803.7	2,040.2	110,371.1	5,112.7	3,667.3	90.4	7,638.9	358.2	1,026.3	67.7	1,284.7	282.7	223.4	417,967.4
Puebla	124,686.8	2,104.7	194,557.0	13,829.5	4,712.8	647.4	10,930.5	5,386.3	528.9	57.2	1,987.2	932.4	511.6	360,872.3
Querétaro	33,435.8	723.5	22,490.5	1,470.3	2,444.4	388.6	7,956.2	4,068.7	1,089.8	309.9	1,283.6	3,122.5	805.6	79,589.4
Quintana Roo	74,533.5	812.6	2,083.9	2,291.3	37.5	5.5	16.0	185.8	36.0	0.8	31.0	63.0	10.7	80,107.6
San Luis Potosí	159,074.0	4,632.2	8,780.7	2,510.6	4,912.3	1,034.7	965.6	1,346.1	820.6	80.9	362.9	477.1	359.8	185,357.4
Sinaloa	37,615.0	1,678.9	5,395.4	2,730.2	3,538.5	1,271.3	14,210.2	103,305.0	127.8	66.7	681.4	1,706.2	4,416.5	176,743.1
Sonora	6,235.8	2,261.4	669.9	64.8	668.0	998.1	1,652.8	6,980.3	14.1	-	20.6	54.9	271.3	19,892.1
Tabasco	63,926.6	2,702.1	10,570.4	5,781.2	119.7	142.0	-	2.5	212.1	18.1	35.4	198.2	3.1	83,711.5
Tamaulipas	45,764.4	3,568.3	3,618.8	2,670.6	4,795.7	1,138.7	3,517.5	32,389.6	91.8	5.2	61.4	509.6	382.9	98,514.5
Tlaxcala	8,756.7	299.8	64,380.2	4,836.9	482.7	17.4	1,583.6	265.0	73.3	50.4	831.3	323.7	16.4	81,917.4
Veracruz	271,053.9	5,934.2	66,767.8	23,379.9	889.5	173.0	1,539.5	538.0	599.8	18.5	299.4	339.4	41.8	371,574.5
Yucatán	113,244.8	544.8	2,525.3	8,244.4	130.4	6.0	86.7	65.1	1,125.9	2.0	35.5	307.4	39.9	126,358.5
Zacatecas	186,056.0	3,163.3	34,916.0	12,125.8	11,609.2	456.9	5,349.0	3,050.1	1,493.1	332.2	1,035.4	1,163.2	256.0	261,006.2
Country total	3,034,788.3	61,064.4	1,351,149.7	624,024.9	87,520.9	16,076.8	158,676.6	280,938.5	19,382.9	2,809.9	27,949.1	65,848.7	24,047.6	5,754,278.4
% of total	52.7	1.1	23.5	10.8	1.5	0.3	2.8	4.9	0.3	<0.1	0.5	1.1	0.4	100.0

[a] R, rain-fed; S, surface irrigated; P, pressurized irrigated; L, landrace seed; H, hybrid seed; WO, without synthetic fertilizers; W, with synthetic fertilizers. [b] Planted area on which maize farmers reported using both surface and pressurized irrigation systems.

Table A18. Estimated planted area (in ha) by maize production system and Mexican state for the autumn-winter growing season based on data from [37].

	Production system[a]													
Mexican state	RLWO	RHWO	RLW	RHW	SLWO	SHWO	SLW	SHW	PLWO	PHWO	PLW	PHW	Other[b]	State total
Aguascalientes	754.7	36.8	329.8	117.5	36.7	4.3	56.6	47.3	16.0	0.7	2.9	92.1	4.4	1,499.8
Baja California	5.9	-	1.5	3.0	-	-	-	5.3	5.0	-	-	-	-	20.6
Baja California Sur	213.5	7.9	2.0	-	80.3	6.5	1.0	24.2	99.0	10.5	127.9	162.3	2.5	737.5
Campeche	5,551.0	146.1	424.4	545.1	0.0	6.3	-	1.2	0.5	-	2.2	5.2	-	6,681.9
Coahuila	312.9	45.3	49.5	1.0	131.9	56.1	18.0	103.3	0.7	-	-	-	-	718.7
Colima	199.2	8.3	221.8	94.8	59.7	1.7	52.2	141.8	17.2	5.0	12.0	6.0	1.0	820.8
Chiapas	30,262.6	94.4	1,388.6	1,372.0	176.5	0.5	97.4	565.0	15.2	-	25.1	145.7	-	34,142.9
Chihuahua	3,637.6	104.1	3,762.6	513.8	144.3	48.4	120.3	416.0	102.5	-	204.4	446.0	76.4	9,576.3
Distrito Federal	43.6	1.0	28.4	6.8	-	-	-	-	0.1	-	3.5	-	-	83.5
Durango	2,880.8	163.0	1,079.0	287.1	403.2	12.5	108.1	142.1	11.4	-	4.9	8.5	250.6	5,351.3
Guanajuato	1,874.5	128.2	2,384.5	1,270.8	129.2	109.0	424.0	3,401.6	22.0	-	179.7	1,764.1	209.8	11,897.3
Guerrero	5,412.1	115.0	2,309.9	1,830.7	196.8	0.6	268.7	475.7	151.9	0.5	38.4	32.6	21.9	10,854.7
Hidalgo	9,027.7	64.2	758.8	46.5	401.8	93.3	314.8	596.6	20.7	7.0	14.1	31.0	175.8	11,552.3
Jalisco	2,116.2	147.9	3,194.0	3,160.7	54.8	15.5	569.4	913.3	71.2	51.1	204.2	212.6	124.8	10,835.7
México	1,723.4	82.4	5,466.8	213.0	175.9	23.2	648.1	118.5	15.5	-	24.5	6.0	1.1	8,498.2
Michoacán	2,174.3	42.4	3,125.7	1,290.3	157.3	28.2	1,570.9	1,230.9	57.3	-	182.8	120.9	248.7	10,229.5
Morelos	57.8	13.9	207.2	454.5	18.0	2.5	115.3	263.9	0.2	-	1.6	14.5	13.5	1,163.0
Nayarit	1,422.1	78.9	694.2	422.0	71.8	-	103.0	803.6	183.1	15.4	330.7	1,021.8	578.0	5,724.7
Nuevo León	1,704.8	655.4	301.0	0.5	144.3	26.4	386.4	1.1	63.4	2.0	1.0	-	2.0	3,288.3
Oaxaca	20,137.2	165.1	6,514.1	468.5	469.4	18.9	1,493.8	75.8	109.3	7.0	150.4	22.6	35.5	29,667.6
Puebla	4,499.5	73.3	4,495.6	378.2	650.9	46.7	2,453.5	292.8	6.9	2.6	48.4	22.5	12.1	12,983.0
Querétaro	3,203.9	48.4	6,688.0	175.9	547.6	15.0	338.1	223.8	35.4	3.7	41.4	174.0	93.9	11,589.3
Quintana Roo	9,018.0	53.4	488.8	267.7	7.0	-	2.2	25.8	2.8	-	8.0	15.5	-	9,889.1
San Luis Potosí	6,272.6	215.5	1,112.7	460.6	252.6	125.1	210.9	443.9	33.5	3.8	138.8	152.8	141.4	9,564.2
Sinaloa	2,043.7	509.7	792.3	3,275.3	1,255.4	976.5	9,788.3	175,307.9	63.6	230.0	137.6	851.0	2,356.4	197,587.8
Sonora	220.9	5.1	5.0	42.6	79.5	26.6	268.4	2,951.8	22.1	2.6	6.0	-	5.0	3,635.7
Tabasco	5,623.7	95.2	636.8	116.9	1.7	-	-	-	4.3	-	-	0.2	-	6,478.8
Tamaulipas	1,551.8	513.3	548.1	1,480.4	375.5	258.7	243.9	1,836.5	-	-	-	163.1	83.8	7,055.0
Tlaxcala	94.8	7.5	472.5	100.7	4.6	-	26.4	7.5	1.0	-	7.6	9.0	-	731.5
Veracruz	33,011.5	450.0	5,460.1	6,977.0	67.5	35.2	78.2	33.8	68.4	6.8	0.8	6.6	0.1	46,195.9
Yucatán	2,478.2	37.3	27.9	223.2	13.7	-	1.8	4.2	65.8	-	-	4.9	4.6	2,861.5
Zacatecas	2,063.5	120.9	1,272.2	219.4	121.5	36.3	133.9	108.7	21.7	7.2	59.0	26.3	7.4	4,198.0
Country total	159,594.0	4,229.6	54,243.9	25,816.5	6,229.4	1,973.9	19,893.2	190,563.8	1,287.8	355.9	1,957.9	5,517.9	4,450.8	476,114.4
% of total	33.5	0.9	11.4	5.4	1.3	0.4	4.2	40.0	0.3	0.1	0.4	1.2	0.9	100.0

[a] R, rain-fed; S, surface irrigated; P, pressurized irrigated; L, landrace seed; H, hybrid seed; WO, without synthetic fertilizers; W, with synthetic fertilizers. [b] Planted area on which maize farmers reported using both surface and pressurized irrigation systems.

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