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Assessing food security and environmental protection in Mexico with a GIS-based Food Environmental Efficiency index

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ABSTRACT

Trends in food security and environmental protection are usually reported separately and at national level, which may be a great limitation to the assessment of regional policies seeking to improve food self-sufficiency, reduce poverty, and at the same time conserve biodiversity. In this study, a spatially explicit, quantitative index relates national and regional trends of food security with trends of land use change in Mexico. Food security was estimated through aspects of food self-sufficiency (production and consumption patterns of basic staple crops and livestock) and food access (based on the marginalization level of households). Land use change was estimated from the official INEGI Land Use and Land Cover cartography. The Food Environmental Efficiency (FEE) Index was calculated for each ecoregion of Mexico over the past 40 years based on an arithmetic count of significant correlations between food security and land use change. Trends at national level suggest a continuous environmental degradation and no improvement in food security except for maize self-sufficiency. At ecoregion level, the FEE index indicates that livestock expansion in the three most affected ecoregions is associated with a decrease in food security and that extensive cropland expansion is associated with an increase in food security in only one of them. The FEE index proved useful for the assessment of land use policies, since it can weigh regional contributions to food security and environmental tendencies.

1. Introduction

The urgent need to address food security in less industrialized countries has led to policies and instruments that may undermine another urgent need, which is to preserve biodiversity and ecosystem services (Verburg et al., 2013; Fuss et al., 2015; Peng et al., 2015). The demand for food, prime materials and biofuels is the main driver of land use changes in the world (Smith, 2013; Verburg et al., 2013; Mbow et al., 2014; Van Wikj, 2014), and has led to the loss of forest to agriculture (Smith, 2013). Food security involves access by all people at all times to food of sufficient quantity and nutritional value for them to lead a healthy and active life (FAO, 2006). This definition includes concepts such as food availability (which requires a balance between population growth and food production), food access (which requires sufficient income to buy a range of goods to guarantee survival), food use (the actual consumption of food) and food stability (regular access to food) (Santos et al., 2014; Frayne and McCordic, 2015). Food security should be considered within an environmental context, especially regarding the consequences of climate change and environmental impacts on the biodiversity and soils (Fuss et al., 2015; Peng et al., 2015; Krishnamurthy et al., 2014). Production practices that drastically affect biodiversity, soil fertility and environmental services are counter-productive in the long run: food production in marginalized areas will decrease, and the risk of extreme natural events will increase (Verburg et al., 2013; Knoke et al., 2013; Mbow et al., 2014; Crist et al., 2017). The negative impacts of food production on ecosystem services must be restricted: future demand for food should be met without extending croplands and grazing lands, and this will entail highly productive agricultural systems that sustain biodiversity (e.g. agro-ecological farming systems; Perfecto et al., 2009). On the other hand, it is argued that poverty of the household has the most direct effect on the environment because it influences the ability to use technology and

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investment for the intensification of cropping where there is a land access constraint (Fisher et al., 2013; Reardon and Vosti, 1995).

Because of its importance in international agendas (e.g. the Zero Hunger Challenge by the United Nations), food security has been assessed and monitored at a range of scales, especially at national level. This can involve various approaches: the balance between availability of food and needs of the population as influenced by production, imports, exports, wastes and aid (FAO, 2012); nutrients and required daily caloric intake (Warren et al., 2015); a combination of the two approaches (Peng et al., 2015); the Global Food Security Index (The Economist Intelligence Unit, webpage 2016) based on production capacity, food distribution, nutritional quality and the ability of the population to pay for food; and adaptation to climate change (e.g. Fuss et al., 2015). In Mexico, food security has achieved prominence with the "Crusade against Hunger" launched by the Federal Government in 2013. This campaign aims to improve food supply to extremely marginalized populations by subsidizing local crop production and increasing smallholder crop yields. A major goal of Mexican land use policy has been, over the past three decades, to increase food security (e.g. Mexican Food System program in 1981; Yúñez et al., 2013) and to reduce activities that contribute to global environmental change (e.g. General Law of Ecological Balance and Environmental Protection 1988). Much debate remains, however, with respect to the rationality of subsidizing some major food production systems while at the same time claiming to protect major biodiversity hotspots (Muñoz-Piña et al., 2008; Schmook and Vance, 2009; Sarukhán et al., 2015). Indeed, the expansion over the past four decades of extensive agricultural land and its impact on highly biodiverse regions has been widely documented (Velázquez et al., 2003; Mas et al., 2004; Bonilla-Moheno et al., 2013; Moreno-Sanchez et al., 2014). This debate tends to overgeneralize contradictions across the Mexican territory. In order to solve for this overgeneralization, we argue that food security and environmental analysis should be spatially disaggregated into coherent ecogeographical units and that spatial indices based on standard national databases should be developed.

Ecoregions (spatial units with similar ecosystem functions, resources and human activities; McDonald et al., 2005) are a useful concept in conservation and planning (Olson et al., 2001; McDonald et al., 2005; Dvorak and Volder, 2010). Seven of the fifteen ecoregions identified in North America are represented in Mexico (Koleff et al., 2011; Fig. 1; Table 1). We propose to develop the Food and Environmental Efficiency (FEE) index, based on food access, food self-sufficiency, and land use/land cover tendencies over the ecoregions of Mexico.

We first estimated food security by the use of proxies for food self-sufficiency and food access, all of which have been used in institutional indicators, for example the Food Security Index from the FAO Hunger Target Global Monitoring (food stability through per capita food production and per capita food supply are employed through food self-sufficiency) and the Global Food Security Index of The Economist Intelligence Unit (food affordability is employed, through marginalization as a proxy of the proportion of the population under the global poverty line). We also estimated Land Use Change Processes (LUCPs) at a national level in Mexico using the Land Use and Vegetation Cover (LUVC) maps produced by the National Institute of Statistics and Geography (INEGI), the official source of land use information in Mexico. The FEE index was based on a correlation analysis between the estimated food security and land-use changes.

This research addresses the following questions: In what ecoregion (s) occurred the greatest advance in food security and did this correspond to the largest expansion of extensive production systems? And: How are the increments or decrements in food security associated with environmental impacts? For example, a hypothesis to be verified in the context of ecosystem degradation would be that an increase in food security (food access, food self-sufficiency, or both) counterbalances a negative environmental impact. In order to answer these questions, we assessed lack of food access through a marginalization index, and food self-sufficiency from data related to annual production and per capita consumption. Then, these variables were correlated with the expansion of extensive agricultural systems derived from the INEGI records of land use and vegetation cover (1976, 1993, 2002, 2007, and 2011).

2. Method

A major purpose of this research is to propose a pragmatic method to estimate environmental efficiency for Food Security policies/tendencies (Fig. 2). The first step was to approximate food security through two major, complementary concepts: food access (or lack of access) and food availability (via food self-sufficiency). One reason for selecting these aspects was the feasibility of their quantitative estimation in a timeframe compatible with the land use data. Second, land-use changes were estimated per ecoregion from national-level cartography. In a third step, food security indicators were related to land-use changes, at national and ecoregion levels, using trend analysis and momentum correlation analysis. Next, a discrete Food Environmental Efficiency (FEE) index was built in each ecoregion as a function of the correlation strength between food security tendencies and environmental preservation tendencies. The index increases with food security increments and with lower environmental damage to the biosphere. Each step of the method is detailed in the following paragraphs.

2.1. Food access

The marginalization concept is related to social exclusion caused by economic growth and inequality (CONAPO, 2012). The marginalization index (MI) is computed by the National Population Council in Mexico (CONAPO, 2012) and is based on indicators associated with population distribution, housing conditions, education level, and labor income. The relationship between marginalization and access to/consumption of food has been acknowledged internationally (Ramos Peña et al., 2007; Cuéllar, 2011), and MI has been the major criterion of Mexican federal programs for the alleged goal of incrementing food access (e.g. the Strategic Project for Food Security; SAGARPA aid programs DICONSA and PROCAMPO). To support this view, it is argued that 80% of the families associated with high and very high marginalization, have an income equal to or lower than the threshold of food poverty (Peralta et al., 2016). Because our food security index is meant to assess the goals of food security policies, we estimated the lack of access to food on the basis of the Marginalization Index. MI was downloaded from the CONAPO website for the following time sequence: 1980, 1995, 2000, 2005 and 2010 (see Table 2). In all dates but 1980, the data was available at locality level. In 1980 we used the information at municipality level. Finally, in each ecoregion, a proxy for food access was computed as the inverse of the average MI.

2.2. Food self-sufficiency

Food self-sufficiency is defined as *"the extent to which a country can satisfy its food needs from its own domestic production"* (FAO, 1999); in this sense, a country tends to food self-sufficiency if it can produce sufficient food to cover its own needs (Clapp, 2017). Based on this concept, food self-sufficiency can be estimated comparing the amount of food production versus the amount of food consumption. Food production was estimated from the annual yields of major crops and livestock (further explained below) obtained at municipality (local government) level, and made available by the Information Service for Agriculture, Food and Fisheries in Mexico (SIAP, 2016). Maize, wheat, rice and bean were the major crops considered in this study, and bovine and ovine the major livestock categories, because of their strategic value for food security and sovereignty in Mexico: They are listed in the Mexican Law of Sustainable Rural Development and Article 180 in this law specifies that their production and supply will be the axes of the

Fig. 1. Ecoregions in Mexico.

national agricultural policy as well as a priority for international agreements and treaties on food security and sovereignty (Diario de la Federación, 2012). The data were collected for 1980, 1993, 2002, 2007 and 2011, considered the best temporal match with the data for land-use changes, and were aggregated at ecoregion level.

Average per capita consumption of the selected crops and livestock is provided by the Department of Agriculture in Mexico (SAGARPA) and the National Chamber of Transformation Industries (García-Urigüen, 2012; Table 3). In order to estimate food consumption per ecoregion, these average data were multiplied by the population of all localities of each ecoregion, according to the INEGI population census collected in 1980, 1995, 2000, 2005 and 2010. The food consumption pattern was assumed similar among ecoregions, but the analysis could be refined using more precise data on food consumption distribution, not available in our case.

Finally, a food self-sufficiency indicator (FSI) was estimated per ecoregion by the normalized difference between food production and food consumption:

$$FSI = (\text{production} - \text{consumption})/\text{consumption}$$

2.3. Land use change processes

Next, we collected the entire set of official INEGI national-level maps of land use and vegetation cover (LUVC INEGI maps) produced at 1:250,000 scale. Although this cartography still lacks accuracy assessment to date, it is considered the most complete and reliable collection of semidetailed land use maps in Mexico (Velázquez et al., 2003; Moreno-Sanchez et al., 2014), due to its continuity since 1976, the interpretation and cartographic long term experience of the INEGI staff, and the relative consistency in the map production process. This set corresponds to the time sequence (five "Series") of 1976 (Series I), 1993 (Series II), 2002 (Series III), 2007 (Series IV) and 2011 (Series V) (Table 3). Although more than 300 land use/land cover categories are represented in this cartography and the classification legend differs from date to date, the five Series are compatible in an aggregated level. We proceeded to the aggregation of all Series to a common set of 29 land use/land cover classes. The consecutive maps (i.e. Series I and II, Series II and III, etc.) were geometrically joined and fused using a Geographic Information System (GIS) into 29 × 29 = 841 change labels, which were then topologically corrected to a legend corresponding

Table 1
Physical features of the ecoregions of Mexico (Koleff et al., 2011).

Ecoregion	No. climatic types	Annual rainfall (mm)	Minimum temperature (°C)	Maximun temperature (°C)	Vertebrate species biodiversity
Great Plains	15	200–1500	16–18	24–26	750
North American Deserts	25	< 50–1000	10–12	24–26	1000
Mediterranean California	8	50–500	10–12	18–20	400
Southern Semi-Arid Highlands	25	200–1500	8–10	22–24	1000
Temperate Sierras	45	200– > 4500	< −2	> 28	1980
Tropical Dry Zone	35	50–2500	12–14	> 28	1890
Tropical Wet Zone	19	600– > 4500	14–16	26–28	1650

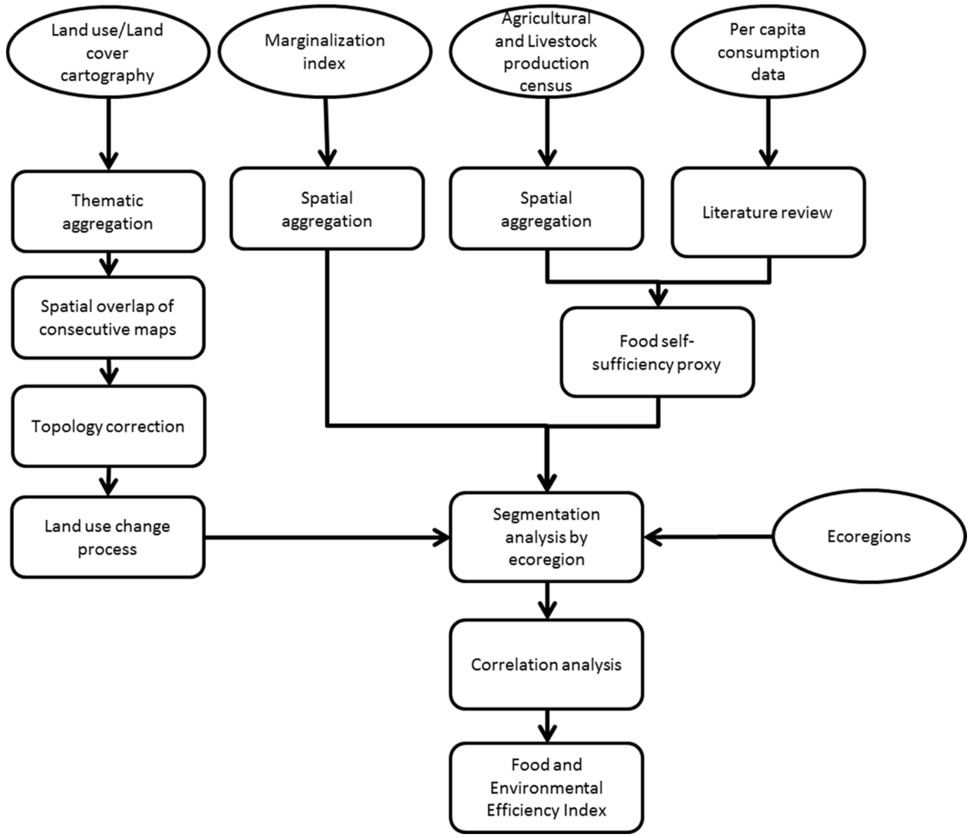

Fig. 2. Flowchart for Food and Environmental Efficiency (FEE) Index computation.

to 8 major land-use change processes:

a.) Permanence of agricultural system
b.) Permanence of vegetation cover
c.) Expansion of agricultural system over vegetation cover
d.) Contraction of agricultural system with natural recovery
e.) Conversion of an agricultural system to another
f.) Degradation of vegetation cover
g.) Urbanization
h.) Undefined (possibly a thematic error of the map)

Due to the scale of the INEGI cartography (Minimum Mapping Unit of about 50 ha), note that the expansion and contraction of land uses is detected only for extensive agricultural systems, not isolated agricultural parcels.

2.4. Food and Environmental Efficiency (FEE) index

2.4.1. Trend analysis

In the first place, a potential relationship between food security (food access and food self −sufficiency estimated earlier) tendencies (FSTs) and land use tendencies (LUTs: e.g. agricultural expansion) was investigated by means of the comparison of trends at the national level and at the ecoregion level.

2.4.2. Correlation coefficient

Then, a correlation coefficient was built in order to seek a strong relationship between food security tendencies (FSTs) and land use tendencies (LUTs) at ecoregion level. The differences in food access and food self-sufficiency were calculated per ecoregion for each time period (e.g. 1980–1995; 1995–2000; 2000–2005; 2005–2010). Then, a Spearman product moment coefficient was computed between FST and LUT. A matrix of correlation coefficients was formed from the comparison between FST (columns) and LUT (rows).

2.4.3. Food and Environmental Efficiency (FEE) Index

Finally, the Food and Environmental Efficiency Index consisted in an arithmetical count of all matrix elements according to the following decision rules based on the comparison between Food Security Tendency (FST) and Land Use Tendency (LUT):

a) The correlation is statistically significant*; FST ** is positive and the correlation coefficient is negative. FEE index incremented by 1.
b) The correlation is statistically significant*; FST** is positive and the correlation coefficient is positive. FEE index incremented by 0.5.
c) The correlation is not statistically significant*, then FEE index unchanged.
d) The correlation is statistically significant*; FST** is negative and the correlation coefficient is positive. FEE index decremented by 0.5.
e) The correlation is statistically significant*; FST** is negative and the correlation coefficient is negative. FEE index decremented by 1.

*Correlation was considered statistically significant if the absolute value of the Spearman coefficient was greater than 0.6 and the associated p-value was < 0.05.

**Tendency is the slope of the linear trend of the variable along time.

3. Results

3.1. National trend of food security

At the national level, the overall tendency of food security in Mexico was as follows. Food access does not have a clear trend (whether positive or negative): in 1980, 1990, 2000 and 2005 it was low (i.e. high marginalization), whereas in 1995 and 2010 it was average (i.e.

Table 2
Characteristics of the Marginalization index (MI) per ecoregion.

Ecoregion	Year	# Observations	MI maximum value
Mediterranean California	1980	2	1.71
	1995	629	2.54
	2000	854	2.79
	2005	480	1.39
	2010	919	3.32
North American Deserts	1980	126	0.71
	1995	7556	1.87
	2000	7423	2.42
	2005	5791	2.50
	2010	6961	4.50
Southern Semi-Arid Highlands	1980	256	1.08
	1995	15987	2.21
	2000	15962	2.39
	2005	14370	2.62
	2010	16703	4.58
Great Plains	1980	71	0.76
	1995	2958	1.56
	2000	2889	2.10
	2005	2032	1.74
	2010	2569	2.65
Tropical Wet Zone	1980	332	2.26
	1995	21296	2.34
	2000	21605	2.93
	2005	19163	3.23
	2010	21472	4.74
Tropical Dry Zone	1980	603	2.59
	1995	22080	2.67
	2000	22411	3.02
	2005	18850	3.23
	2010	21686	6.35
Temperate Sierras	1980	1002	2.77
	1995	35129	2.80
	2000	35989	3.05
	2005	32470	3.23
	2010	37083	5.77

average marginalization). In terms of food self-sufficiency, maize and bean consumption reduced drastically from 1980 to 2011 (by 58% and 46% respectively), while maize production increased by 37% but bean production decreased by 39%. The consumption of other crops remained relatively stable while wheat production increased by 30% and rice production decreased by 60%. Meanwhile, the consumption of bovine meat remained relatively stable and the consumption of ovine meat nearly tripled while their production steadily increased (by 70% and 154% respectively) (Table 4). Maize production, historically lower than maize consumption, tended to increase (as reported by SAGARPA, 2016) and get closer to the consumption level (FSI increased from −0.69 to −0.4). By contrast, for all other crops self-sufficiency has tended to decrease (from −0.26 to −0.51 for wheat, from −0.35 to −0.57 for bean, and from −0.21 to −0.86 for rice). Livestock production in 1980 almost met the theoretical demand for meat in Mexico. Between 1980 and 2002, consumption of bovine meat increased and the FSI decreased in spite of sustained increased production. However, the consumption subsequently stabilized, and the FSI increased to −0.13 in 2011. Meanwhile, the increase in consumption of ovine meat tended to maintain a negative balance of self-sufficiency in the final three decades (−0.41 in 2011). In synthesis, at national level there is no clear positive or negative trend in food access but there has been a trend towards a loss of food self-sufficiency with respect to all crops and livestock with the exception of maize and, recently, bovine meat (Table 4).

Table 4
Food self-sufficiency indicator (FSI) in Mexico. Population data from INEGI census.

Crop/ livestock	Year	Annual per capita consumption (kg)	Annual production (ton)	Annual consumption (ton)	FSI
Maize	**1980**	568.1	12,374,400	39,965,835	−0,69
	1993	363.4	18,125,263	33,305,610	−0,46
	2002	241.50	18,659,820	25,768,050	−0,28
	2007	290.0	23,595,189	32,915,000	−0,28
	2011	239	16,996,191	28,536,600	−0,40
Wheat	**1980**	53.6	2,784,914	3,770,760	−0,26
	1993	59.9	3,582,450	5,489,835	−0,35
	2002	58.82	3,225,695	6,276,094	−0,49
	2007	57.6	3,507,959	6,537,600	−0,46
	2011	61.6	3,623,078	7,355,040	−0,51
Rice	**1980**	8.0	445,364	562,800	−0,21
	1993	7.1	287,180	650,715	−0,56
	2002	9.18	215,498	979,506	−0,78
	2007	10.5	294,697	1,191,750	−0,75
	2011	9.7	173,460	1,158,180	−0,85
Bean	**1980**	20.6	935,174	1,449,210	−0,35
	1993	14.5	1,287,573	1,328,925	−0,03
	2002	16.28	1,533,036	1,737,076	−0,12
	2007	10.0	991,126	1,135,000	−0,13
	2011	11.1	566,146	1,325,340	−0,57
Bovine meat	**1980**	15.9	1,065,070	1,118,565	−0,05
	1993	15.5	1,256,478	1,420,575	−0,12
	2002	19	1,467,569	2,027,300	−0,28
	2007	18.6	1,633,901	2,111,100	−0,23
	2011	17.3	1,802,759	2,065,620	−0,13
Ovine meat	**1980**	0.3	22,270	21,105	0,06
	1993	0.5	28,672	45,825	−0,37
	2002	0.84	38,195	89,628	−0,57
	2007	0.7	48,412	79,450	−0,39
	2011	0.8	56,429	95,520	−0,41

3.2. National trend of land use change

In terms of land-use change, croplands and grazing land expanded at a relatively stable rate of 300,000–366,000 ha/year between 1976 and 2007 (Table 5), associated to some degree with the increased production of maize, wheat and bovine meat, as well as with the expansion of the extensive type of livestock systems. Then, between 2007 and 2011, the increase in cropland and grazing land fell to 175,000 ha/year (Table 5). Additionally, crops and livestock systems contracted spatially (at rates about half the expansion rate), and then expanded again in other directions (Fig. 3), creating agricultural frontiers with stages of vegetation recovery that differed from previous expansions. In synthesis, a continuous expansion of croplands and grazing lands occurred at the expense of natural ecosystems (already reported in previous studies such as Mas et al., 2004 and Mas et al., 2009), and, beyond the conversion to croplands and grazing lands, a substantial portion of the territory was converted to secondary vegetation as a result of a past land use change, an effect on biodiversity which is usually overlooked by official national and FAO summary reports.

Table 3
Characteristics of the land use and vegetation cover cartography.

Land use and vegetation cover maps	Name	Sources of spatial data	Dates	Methods
1976	Series I	Aerial photographs	1968–1986	Field work and photointerpretation
1993	Series II	Landsat TM	1993	Interpretation of satellite images and field work to update 1976 map
2002	Series III	Landsat ETM	2002–2003	Interpretation of satellite images and field work
2007	Series IV	SPOT-5	2007–2008	Interpretation of satellite images and field work
2011	Series V	Landsat TM	2011	Interpretation of satellite images and field work

Table 5
Expansion and contraction of food production systems.

Land use change	1976–1993		1993–2002		2002–2007		2007–2011	
	Area (million ha)	Annual rate	Area (million ha)	Annual rate	Area (million ha)	Annual rate	Area (million ha)	Annual rate
Cropland expansion	5.2	305,882	3	333,333	1.8	360,000	0.7	175,000
Cropland contraction	2.7	158,824	1.7	188,889	1	200,000	0.5	125,000
Grazing land expansion	5.8	341,176	3.3	366,667	1.6	320,000	0.7	175,000
Grazing land contraction	1.9	111,765	1.7	188,889	1	200,000	0.3	75,000

These results raise the question of how food security policies have related to environmental protection policies in the last three decades, and how this relationship, understood in a spatial framework, could be improved.

When disaggregated per ecoregion, food access values (computed as the inverse of marginalization) remained low for five of the seven ecoregions in Mexico: North American Deserts, Southern Semi-Arid Highlands, Tropical Wet Zone, Tropical Dry Zone and Temperate Sierras; factors in this deficiency included insufficient access to education, inadequate housing, overcrowded households, and a perception of insufficient monetary income (CONAPO, 2012). In contrast, food access was high in Great Plains and very high in Mediterranean California (Fig. 4, Table 6). Additionally, most ecoregions were found food dependent (negative food self-sufficiency indicator – FSI: Fig. 5) for basic crops. As expected, FSI was positive for ecoregions where productive systems of the crop are most abundant: wheat and bean in North American Deserts, and rice in the Tropical Wet Zone. In spite of high productivity in the Temperate Sierras, maize is not self-sufficient there, maybe because of the very high consumption (major population concentration of the country). Instead, maize tends to self-sufficiency in the Tropical Dry Zone (Fig. 5a–d). The FSI for bovine production was high in the Tropical Wet Zone, probably owing to the widespread presence of extensive livestock systems in that ecoregion (Fig. 5e). In terms of ovine production, none of the ecoregions was self-sufficient (Fig. 5f).

3.3. Trend of land use change at eco-region level

The major expansion of production systems occurred between 1976 and 1993, mostly in the Tropical Wet Zone and in the Great Plains (Fig. 3). The largest accumulated (from 1976 through to 2011) crop expansion occurred in the Tropical Wet Zone and the Temperate Sierras (Fig. 6), representing 51% of the total national crop expansion. The corresponding ecosystem reduction mostly affected secondary vegetation cover (44.25%), then scrublands (31.25%) and then primary vegetation cover (24.5%). In terms of grazing land expansion, the most affected ecoregions were the Tropical Wet Zone and the Tropical Dry Zone, where 58% of all changes occurred. Loss of secondary vegetation represented 59.5% of the loss of natural ecosystems in these two ecoregions, followed by primary vegetation (23.25%) and scrublands (17.25%).

Fig. 3. Expansion and contraction of food production systems 1976–1993.

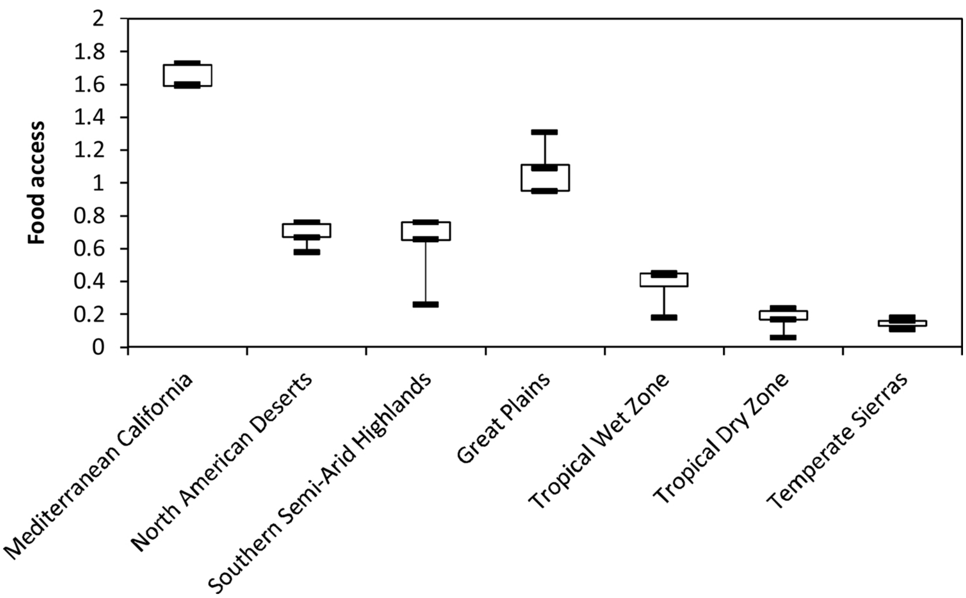

Fig. 4. Food access per ecoregion in Mexico 1980–2010 (box plots computed from the inverse values of the CONAPO Marginalization Index).

3.4. Possible relationships between food security and land use change by trend analysis

According to our national level analysis, the continuous expansion of croplands and grazing lands reported earlier does not seem to be associated with a positive trend in terms of food access. At ecoregion level, we found that food access remained low in the two ecoregions most affected by the expansion of croplands as reported earlier (Tropical Wet Zone and Temperate Sierras). Similarly, food access has improved neither in the Tropical Wet Zone nor in the Tropical Dry Zone, where the greatest grazing land expansion occurred. Both of these ecoregion-level results corroborate the national-level analysis whereby the hypothesis of an improvement of food access as a consequence of the expansion of extensive agricultural systems seems to prove false.

Likewise, at national level, no improvement of food self-sufficiency has been registered for all crop types but maize, and for ovine production. By contrast, the national food self-sufficiency indicator (FSI) of maize tended to increase over the entire time period (despite remaining negative) and the national FSI of bovine tended to increase since 2002 (despite remaining negative). On the other hand, the two ecoregions most affected by the expansion of croplands as reported earlier (Tropical Wet Zone and Temperate Sierras) are characterized by negative self-sufficiency indicators (FSI) for all crops except rice in the Tropical Wet Zone. In the case of rice production however, almost confined to the Tropical Wet Zone (which explains the positive self-sufficiency of rice in that ecoregion), its contribution to the expansion of croplands is probably very low compared with that of other crops. By contrast, food self-sufficiency was found positive for bovine meat in the Tropical Wet Zone, one of the two ecoregions most affected by the expansion of extensive livestock systems. In this case, the ecoregion-level analysis seemed to negate the hypothesis suggested by national level analysis that an improvement in food self-sufficiency could be a consequence of the expansion of extensive maize production.

In synthesis, the expansion in agricultural systems throughout the four last decades does not seem to have been accompanied by a substantial increase in food access. The expansion of croplands in ecoregions with the highest annual rates does not seem to have been accompanied by a substantial increase in self-sufficiency either, even for maize. By contrast, the expansion of grazing lands in the Tropical Wet Zone may have been accompanied recently by an improvement in self-sufficiency of bovine meat in the country. In order to explore relationships between food security and land use change over the entire time period, and for the entire set of food security indicators, we analyzed the correlation matrix between these tendencies (Table 7).

3.5. Relationships between food security and land use change by correlation analysis

The Food Environmental Efficiency (FEE) index was calculated for agricultural systems and reflects systematic correlation behavior over time for the complete set of indicators. FEE is the sum of all columns in Tables 8 and 9 (see the methods section). According to this index, while extensive cropland systems expanded in North American Deserts and the Tropical Wet Zone, the environmental impact was accompanied by reduced food security in many aspects (strongly negative values, see Table 8). Similarly, the expansion of livestock systems was in fact mostly accompanied by a loss of food security (non-positive FEE values for all ecoregions except Temperate Sierras, see Table 9). By contrast,

Table 6
Average Food Access (AFA) for different periods of time per ecoregion.

Ecoregions	AFA 1980	AFA 1995	AFA 2000	AFA 2005	AFA 2010	All-period AFA	AFA category[a]
Mediterranean California	1.6	1.59	1.73	1.72	1.59	1.64	Very high
North American Deserts	0.58	0.67	0.76	0.75	0.67	0.69	Low
Southern Semi-Arid Highlands	0.26	0.76	0.66	0.65	0.76	0.62	Low
Great Plains	1.31	0.95	1.11	1.09	0.95	1.08	High
Tropical Wet Zone	0.18	0.45	0.44	0.37	0.45	0.38	Low
Tropical Dry Zone	0.06	0.17	0.22	0.24	0.17	0.17	Low
Temperate Sierras	0.18	0.16	0.11	0.13	0.16	0.15	Low

[a] AFA was computed as the inverse of the average value of CONAPO Marginalization Index (CONAPO, 2012).

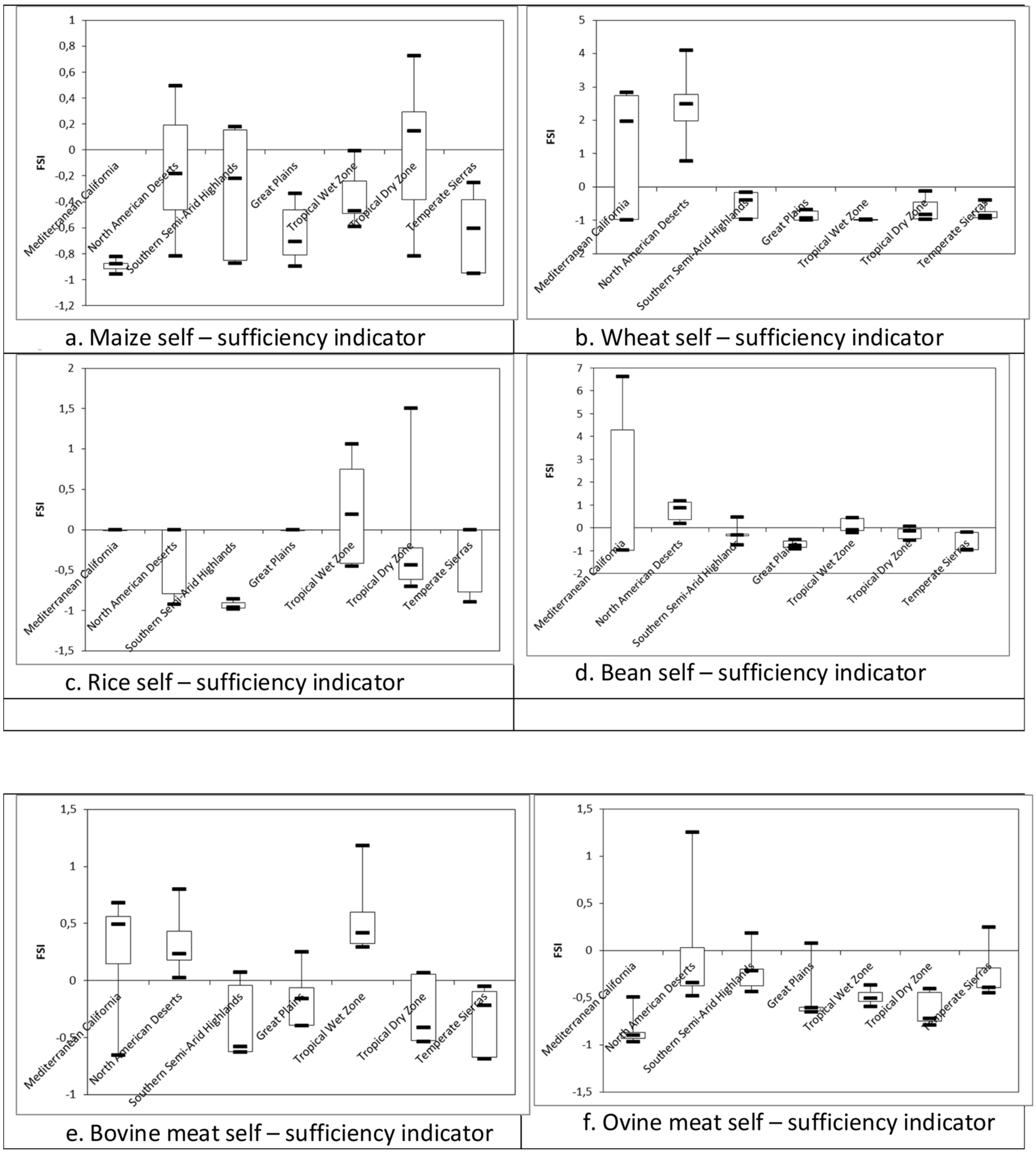

Fig. 5. Distribution of the food self-sufficiency indicator per ecoregion over the 1980–2010 time period (5 dates). a: Maize; b: Wheat; c: Rice; d: Bean; e: Bovine meat; f: Ovine meat. Plot marks indicate minimum and maximum values, 25th and 75th quartile and median value (middle line). Food self – sufficiency is calculated as [(production – consumption)/consumption]. A positive self – sufficiency median value indicates that a majority of the 5 observed dates has shown self – sufficiency in that ecoregion (i.e. food production was higher than food consumption).

food security increased (positive FEE values) in three ecoregions (Southern Semi-Arid Highlands, Great Plains and Temperate Sierras) when croplands expanded (see Table 8). Further comparisons and analysis per ecoregion can be achieved by the reader using these tables and indices.

4. Discussion

4.1. Trends of land use change

Among sub-tropical countries, Mexico is recognized for its active debate on the expansion of agricultural production systems onto areas of natural ecosystems (Muñoz-Piña et al., 2008). Recent discourses in Mexico have announced the stabilization of agricultural frontiers since the early 2000 s (Balvanera et al., 2009). But these discourses are based on the account of net area differences over time at the national level (SIACON, 2013) computed from the official INEGI maps of land use and vegetation cover (LUVC INEGI maps), as is reported by the Global Forest Resources 2010 FAO report (FAO, 2010).

In our study, the expansion and contraction of agricultural systems are quantified and show a considerable amount of land under dynamic pressure from the agricultural frontier in spite of the reduction of the expansion rate by about half for the 2007–2011 time period. Uncertainty did affect our area estimates of Land Use Change Processes (LUCP), due to inaccuracies of the official LUVC INEGI maps which propagate to land use change maps. Unfortunately, these inaccuracies have not been estimated through a rigorous accuracy assessment to date by INEGI (Mas et al., 2016). Preliminary results from a rigorous accuracy assessment study by the authors (unpublished data) of some of these land use change maps suggest a consistent overestimate of the magnitude of expansion as well as contraction rates of agricultural systems; the overestimate is attributed to false changes corresponding

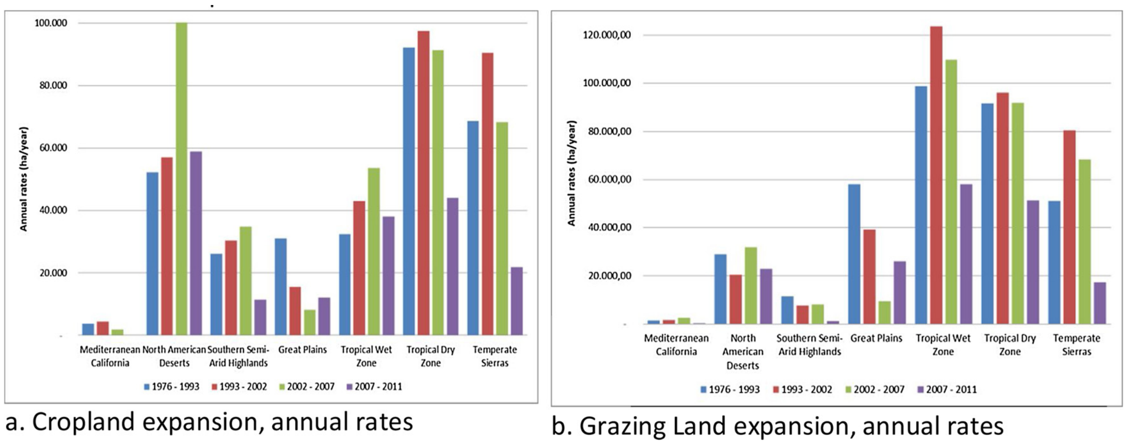

Fig. 6. Annual rates of expansion of production systems.

to distinct acquisition conditions of the set of satellite imagery from one series to the next, therefore the overestimate should be somehow consistent along the entire historical sequence. Consequently, the bias should not affect much our ecoregion level trend analysis since the relevant LUCPs were assimilated as constant expansion and contraction over time. Since the Spearman correlation coefficient is sensitive to subtler variations of land use changes from one period to the next, the FEE index may be affected by this bias.

4.2. Contribution of single factor trend analysis to land use policy in Mexico

The results of the trend analysis (Section 3.5) should be valuable to land use policy in Mexico; For the vast majority of food security factors, the expansion of extensive production systems do not relate to a clear, quantitative improvement, a result which should be considered in the assessment of agricultural policies over 40 years.

Additionally, the improvement in maize self-sufficiency registered at national level over this period of time may in fact be associated with other causes than to the expansion of croplands, since our trend analysis at ecoregion level shows that no such improvement occurred in ecoregions mostly affected by this cropland expansion. This result warns of possible limitations of traditional national – level analysis alone. On the other hand, the improvement in bovine meat self-sufficiency registered at national level over the period 2002–2011 could indeed be associated to the expansion of grazing lands in the Tropical Wet Zone, a result which corroborates well-known conversion tendencies of agricultural activities to the grass fed beef industry nationwide, for its economic benefits to local peasants and investors (Schmook and Vance, 2009; Sarukhán et al., 2015). However, this expansion in the Tropical Wet Zone is environmentally unsustainable, owing to the very high biodiversity, acting itself as a buffer for the local population against environmental and economic risks (Mijatović et al., 2013). Now, the concept of bovine meat self-sufficiency (based on the actual consumption trend of the population) can be seriously challenged as an adequate contributor to food security in Mexico with respect to other contributors: the overconsumption of meat is one of the main challenges of public health policies in Mexico (Campos-Pérez et al., 2016), causing major diseases such as diabetes and hypertension.

Also, because they rely on available time consistent data, our proxies for food access and food self-sufficiency may not reflect some important features of these concepts. In the case of food access, rural households labeled as highly marginalized (and hence with low "food access") may in fact benefit from a well-balanced and sufficient diet because of adequate livelihood strategies which include access to goods from subsistence agriculture and hunting. These livelihood strategies relate to major aspects of food security such as the contribution of smallholder agriculture and agro-ecology (Bermeo et al., 2014; Bermeo and Couturier, 2017), and yet are not reflected in the marginalization index. In other official data (e.g. the agricultural census), some variables may relate to this feature although the nationwide availability of the data (only two dates) is insufficient for its incorporation in our study. Consequently, food access (including subsistence livelihood strategies) in this research may be underestimated in ecoregions with high rural population (e.g. the Tropical Wet Zone, the only ecoregion where the rural population is a majority) with respect to food access in ecoregions with predominantly urban population (e.g. Temperate Sierra).

In the case of food self-sufficiency, consumption was computed on the basis of an average value per capita. This estimate could be improved by using different figures for rural and urban settings within an ecoregion. According to García-Urigüen (2012), daily per capita intake of maize is 148 g in cities greater than 100,000 inhabitants while it is 234.2 g in localities smaller than 2500 inhabitants, although this is difficult to generalize over time. Consequently, in this research, maize self-sufficiency may be overestimated in ecoregions with predominantly rural population (e.g. Tropical Wet Zone) and underestimated in ecoregions with predominantly urban population (note that this food self-sufficiency bias is opposite to the food access bias commented above).

In this sense, each factor taken alone (such as single crop/single livestock self-sufficiency, or food access) fails to accurately represent the concept of food security in the country. The Food and Environmental Efficiency (FEE) index allows a more holistic (perhaps more balanced for a mix of rural and urban settings) estimate of food security using 7factors of food security rather than one.

4.3. Contribution of the Food and Environmental Efficiency (FEE) index to land use policy in Mexico

According to the FEE index, in all but two ecoregions, food security decreased while grazing lands expanded (see section 3.6), and this decrease was especially high in the Tropical Wet Zone (FEE index value of −1.5). This result challenges the ecoregion single factor analysis above (Section 4.2), is contradictory to the increment in food security suggested by a national level trend analysis, and warns of possibly highly negative consequences of land use policies aiming at promoting and sustaining livestock systems for the sake of national food security (the case of the most influential agricultural incentive programs ongoing for 25 years in Mexico), especially in the Tropical Wet Zone.

Likewise, food security decreased sharply with cropland expansion in the Tropical Wet Zone (FEE = −3) and North American Deserts (FEE = −2.5). Instead, cropland expansion in three ecoregions (Southern Semi-Arid Highlands, Great Plains and Temperate Sierras) was associated with an increment of food security (positive FEE values). This result was not perceived by trend analysis and suggests that these

Table 7
Correlation between the food security trend (FST) and the land use trend (LUT) along the 1976–2011 time period. These results are based on the Spearman product-moment correlation between food security and land use variables (5 dates). Significance levels of the correlation are shown as *.01 < P < .05, ** P = < .01 and ns P > 0.05.

Land use change	Ecorregion	Cropland expansion	Grazing land expansion	Food access	Food self-suffiency for Maize	Food self-suffiency for Wheat	Food self-suffiency for Rice	Food self-suffiency for Bean	Food self-suffiency for Bovine meat	Food self-suffiency for Ovine meat
Cropland expansion	Mediterranean California	1.00	0.40 ns	−0.96**	−0.60*	0.20 ns	No production	0.96**	−0.57 ns	0.35 ns
	North American Deserts	1.00	0.60*	0.60*	0.60*	−0.60*	No production	−0.60*	−0.40 ns	0.40 ns
	Southern Semi-Arid Highlands	1.00	0.80**	−0.60*	0.40 ns	−0.60*	0.94**	0.40 ns	0.20 ns	0.20 ns
	Great Plains	1.00	0.96**	−0.96**	0.20 ns	−0.20 ns	No production	−0.96**	0.40 ns	−0.40 ns
	Tropical Wet Zone	1.00	0.40 ns	0.80**	−0.40 ns	−0.60*	0.40 ns	0.60*	0.05 ns	0.40 ns
	Tropical Dry Zone	1.00	0.96**	0.40 ns	0.60*	−0.20 ns	−0.15 ns	0.40 ns	−0.80**	0.20 ns
	Temperate Sierras	1.00	0.96**	−0.60*	0.20 ns	−0.96**	No production	−0.40 ns	−0.40 ns	0.20 ns
Grazing land expansion	Mediterranean California	0.60*	1.00	−0.60*	−0.40 ns	0.80**	No production	0.40 ns	0.20 ns	0.96**
	North American Deserts	0.60*	1.00	−0.20 ns	0.80**	−0.80**	No production	0.40 ns	0.60*	−0.96**
	Southern Semi-Arid Highlands	0.80**	1.00	0.60*	0.60*	0.05 ns	−0.40 ns	0.80**	−0.20 ns	0.05 ns
	Great Plains	0.96**	1.00	−0.80**	0.60*	−0.05 ns	No production	0.96**	0.80**	−0.40 ns
	Tropical Wet Zone	0.40 ns	1.00	−0.05 ns	−0.40 ns	−0.96**	0.60*	0.96**	−0.96**	0.60*
	Tropical Dry Zone	0.96**	1.00	0.40 ns	0.96**	0.20 ns	−0.20 ns	0.96**	0.20 ns	0.40 ns
	Temperate Sierras	0.96**	1.00	−0.4 ns	0.40 ns	−0.96**	No production	0.05 ns	−0.60*	0.40 ns

ecoregions are more suitable for sustaining cropland than the Tropical Wet Zone. National trend analysis denoted an improvement of maize self-sufficiency but failed to capture the contribution of other crops in the estimation of food security, a contribution which was incorporated in the FEE index.

Finally, one should beware of erroneous interpretations associated with increments in food security through the FEE index analysis. One should keep in mind that getting closer to the balance between food production and food consumption does not mean that the Mexican population (or in this case the population of an ecoregion) is actually consuming the food produced in Mexico (in the same ecoregion). It only means the Mexican society *could* mostly consume the food produced nationally or regionally. For example, cropland expansion and the increment in food security obtained in the Southern Semi Arid Highlands, Great Plains and Temperate Sierra could be explained by the incremented production of food for exportation, while the Mexican population in these ecoregions might in fact experience a lack of access to food produced in these ecoregions. While food security policies may drive some of the increment of food production in Mexico, probably stronger drivers are associated with the demand for exportation of food from Mexico, because of the specific, restricted position of Mexico within the globalized food distribution network. Likewise, the increment of beef meat production in the Tropical Wet Zone could be associated with more exportation to the USA, while more imported beef from elsewhere would be consumed by the Mexican population. In this sense, the FEE indicator presented in this research, based on a simple food self sufficiency indicator, reflects theoretical food self-sufficiency and not food independency; data on importation/exportation patterns should be incorporated for interpretation of the results in terms of real fluxes for food production − consumption.

5. Conclusion

The main object of this research is to set a baseline in Mexico for long term trend studies in food security and land use change, in order to establish possible relationships that are useful for national level land use policies. To this respect, the contribution of this article is multifold:

In the first place, we present the first land use change assessment in Mexico for the 35 year time span 1976–2011, focused on extensive agricultural activity versus natural ecosystems. As was shown by studies on time periods until 2007 (Mas et al., 2004; Mas et al., 2009), a continuous expansion of croplands and grazing lands at the expense of natural ecosystems occurred nationwide. Beyond the conversion to croplands and grazing lands, we evidenced that a substantial portion of the territory was converted to secondary vegetation as a result of past land use changes, an effect on biodiversity which is usually overlooked by official national and FAO summary reports.

Second, a national level food security trend analysis revealed that there is stagnation of food access nationwide (low to average food access) in the 1976–2011 time period, and there has been a trend towards a loss of food self-sufficiency with respect to all crops and livestock with the exception of maize and, only recently, bovine meat.

Third, trend analysis at ecoregion level mostly confirms the trend at national level: low food access and negative food self-sufficiency for most crops and livestock in each ecoregion. However, in the case of maize, the hypothesis by which the expansion of cropland throughout the country could have triggered an improvement in maize self-sufficiency at national level, is deterred at ecoregion level: 51% of the accumulated cropland expansion occurred in the Tropical Wet Zone and in the Temperate Sierras (inhabited by the largest concentration of the Mexican population), where maize self–sufficiency has not improved and remained largely negative. Maize self-sufficiency has improved instead in ecoregions such as the Tropical Dry Zone, where the expansion of cropland was much lower, with the possible implication that other factors caused the improvement of maize self-sufficiency in the country.

Table 8
The Food Environmental Efficiency (FEE) index for cropland expansion. The FEE index is computed as the sum of all columns.

Land use change	Ecoregion	Food access	Food self-suffiency for Maize	Food self-suffiency for Wheat	Food self-suffiency for Rice	Food self-suffiency for Bean	Food self-suffiency for Bovine meat	Food self-suffiency for Ovine meat	FEE index (Sum)
Cropland expansion	Mediterranean California	−0.5	1	0	0	−0.5	0	0	0
	North American Deserts	−1	0.5	−1	0	−1	0	0	−2,5
	Southern Semi-Arid Highlands	1	0	−1	0.5	0	0	0	0.5
	Great Plains	−0.5	0	0	0	1	0	0	0.5
	Tropical Wet Zone	−1	0	−1	0	−1	0	0	−3
	Tropical Dry Zone	0	−1	0	0	0	0.5	0	−0.5
	Temperate Sierras	−0.5	0	1	0	0	0	0	0.5

Fourth, with the more holistic analysis (seven factors of food security) using the Food Environmental Efficiency (FEE) index, we found that major cropland expansions in the Tropical Wet Zone and in North American Deserts were in fact associated with greatly reduced food security there (highly negative FEE values), implying re-thinking of extensive cropland expansion as an incentive for food security. The FEE analysis also deterred a possible interpretation of national level trends that food security might have improved since 2002 due to the enhancement of bovine meat self-sufficiency; indeed, the expansion of grazing lands correlated with decreasing food security for all but two ecoregions. In the meanwhile, cropland expansion did correlate with increasing food security for three ecoregions, meaning that cropping is more likely associated with food security in Mexico than livestock activity.

Beyond the value of the above results for Mexico, the ecoregion level trend analysis and the FEE index proved useful to confirm or correct traditional, single factor trends detected by a national level analysis. These tools are replicable with similar or updated official data for future assessment of food security and environmental protection, and are perhaps more adequate for policy application and assessment than existing analytic tools. In this sense, the FEE index is proposed as a complement to existing national-level food security indices (FAO Hunger Target Global Monitoring program or Global Food Security Index from the Economist Intelligence Unit). Parallel studies of our research team focus on the spatial footprint of nutrition security for Mexico City and the Mexican Central region.

For the purpose of enhancing public policies toward improving community wealth, infrastructure, distribution of household assets, agro-biodiverse forms of food production, nutrition security (Bermeo et al., 2014; Fisher et al., 2013; Tscharntke et al., 2012; Crist et al., 2017), it is important to substantially broaden the scope of food access and food self-sufficiency as reflected by currently available data, because some of these aspects are ignored in the FEE index presented in this research. In this sense we suggest that public institutions such as SAGARPA and INEGI generate and publish more frequently and more detailed data on smallholder agriculture, livelihood production strategies and consumption patterns over time and space, as specified in some former census formats (e.g. Coffee Production census; Agricultural census).

Among limitations of ecoregion based indices for policy making, there certainly are obstacles to the implementation of public policies to agricultural systems at ecoregion level; the diversity of land ownership types, the disparity of socio-economic and ethnic backgrounds within an ecoregion, and rural demographic pressure, are all possibly challenging factors where the involvement of actors at local to regional scales is required. To this regard, the social-ecological spatial framework have been proposed as better suited for driver analysis and implemented in previous studies (Castellarini et al., 2014; Leslie et al., 2015). In order to assess specific food security policies or tendencies, the FEE index, or an adaptation of the FEE index, could be computed within this more detailed framework.

The arithmetic computation of the FEE index makes it scalable to more, or more adequate, food security factors (e.g. poverty types, nutrition security within food self-sufficiency, etc., Poulsen et al., 2015; Crist et al., 2017), allowing several ways to improve the quality of the index. Also, the robustness of the FEE index may be enhanced when the accuracy of the national LUVC maps and corresponding change maps in Mexico is estimated and known. This could be achieved using accuracy assessment methods developed for this purpose in Mexico (Couturier et al., 2012; Mas et al., 2016) and already implemented on national cartography (Couturier et al., 2010 as well as unpublished data). Because the FEE index is more holistic (multifactorial) but more sensitive to data uncertainty than trend analysis, we suggest both be applied as complementary tools. As a consequence of the above, ecoregion level trend analysis and FEE index could provide a useful baseline for food security and land use tendencies in subtropical countries with similar socioeconomic and environmental challenges.

Table 9
The Food Environmental Efficiency (FEE) index for grazing land expansion. The FEE index is computed as the sum of all columns.

Land use change	Ecoregion	Food access	Food self-suffiency forMaize	Food self-suffiency for Wheat	Food self-suffiency for Rice	Food self-suffiency for Bean	Food self-suffiency for Bovine meat	Food self-suffiency for Ovine meat	Sum
Grazing expansion	Mediterranean California	−0.5	0	−0.5	0	0	0	−0.5	−1.5
	North American Deserts	0	0.5	−1	0	0	0.5	−1	−1
	Southern Semi-Arid Highlands	1	−0.5	0	0	−0.5	0	0	0
	Great Plains	−0.5	−0.5	0	0	1	−0.5	0	−0.5
	Tropical Wet Zone	0	0	−0.5	−0.5	−0.5	0.5	−0.5	−1.5
	Tropical Dry Zone	0	−0.5	0	0	−0.5	0	0	−1
	Temperate Sierras	0	0	0.5	0	0	0.5	0	1

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