Review

Soil Organic Carbon Depletion from Forests to Grasslands Conversion in Mexico: A Review

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Abstract: Land use change from forests to grazing lands is one of the important sources of greenhouse gas emissions in many parts of the tropics. The objective of this study was to analyze the extent of soil organic carbon (SOC) loss from the conversion of native forests to pasturelands in Mexico. We analyzed 66 sets of published research data with simultaneous measurements of soil organic carbon stocks between native forests and pasturelands in Mexico. We used a generalized linear mixed effect model to evaluate the effect of land use change (forest versus pasture), soil depth, and original native forest types. The model showed that there was a significant reduction in SOC stocks due to the conversion of native forests to pasturelands. The median loss of SOC ranged from 31.6% to 52.0% depending upon the soil depth. The highest loss was observed in tropical mangrove forests followed by highland tropical forests and humid tropical forests. Higher loss was detected in upper soil horizon (0–30 cm) compared to deeper horizons. The emissions of CO_2 from SOC loss ranged from 46.7 to 165.5 Mg CO_2 eq. ha^{-1} depending upon the type of original native forests. In this paper, we also discuss the effect that agroforestry practices such as silvopastoral arrangements and other management practices like rotational grazing, soil erosion control, and soil nutrient management can have in enhancing SOC stocks in tropical grasslands. The results on the degree of carbon loss can have strong implications in adopting appropriate management decisions that recover or retain carbon stocks in biomass and soils of tropical livestock production systems.

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1. Introduction

Human food and energy production practices in the past decades have significantly altered natural biogeochemical cycles [1–3]. Increasing concentrations of carbon dioxide (CO_2) and other greenhouse gases (GHGs) in the atmosphere is one of the consequences of such alterations [4]. Although the principal source of GHGs is the energy sector, agriculture and land use change significantly contribute to global emissions [1,5]. The global annual GHG emissions from agriculture, forestry, and other land use (AFOLU) in the year 2010 was 10.3 ± 0.9 Pg CO_2 equivalent year^{-1}, contributing to 21% of total anthropogenic GHG emissions, of which 52%% came from agriculture including livestock production [6].

Livestock production has expanded widely in the last few decades and currently occupies 67.7% (3315 million hectares) of the world's total agricultural land [7]. Land use change related to the extension of pasturelands has been an important source of GHG emissions in many parts of the tropics [8–12]. Nearly 20.8 million hectares of native forests were converted to pasturelands in Mexico alone during the period of 1993 to 2000 [13]. The net annual GHG emissions from biomass and soil organic carbon (SOC) loss related to land use change in Mexico were 64.5 Tg CO_2 year^{-1} and 30.3 Tg CO_2 year^{-1}, respectively, during the period of 1993 to 2002 and 2003 to 2007 [8]. About 60% of these emissions have been attributed to the conversion of native forests to pasturelands [8,13]. Such conversion of native forest ecosystems to cultivated pasturelands has tremendously increased the environmental footprints of the livestock production sector [9,14,15].

Grasslands, including native and cultivated pasturelands, contain about 20% of the world's SOC stocks [16], but a huge amount of SOC is lost in the conventionally managed treeless pasturelands [17]. In Latin America, an estimated 200 million hectares of grazing land is severely degraded with reduced vegetative cover and loss of soil organic carbon [18]. Treeless pasture systems are vulnerable to losing SOC due to the increased seasonal variability of the soil moisture regime and CO_2 emissions from soil organic matter decomposition [17,19]. Changes in soil biology and soil aggregate properties result in the loss of organic carbon in extensive treeless pasturelands [20,21].

The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) identified the substantial role of SOC sequestration in mitigating GHG emissions (Smith et al., 2014). The amount of C stored in the SOC pool of an ecosystem depends on the dynamic equilibrium of gains and losses [11]. The soil C gain in natural ecosystems occurs principally by the process of litterfall, tree mortality, root turnover, and decomposition of all organic materials [11,22,23]. Soil organic matter decomposition and lateral carbon flow are the principal processes of carbon loss in such ecosystems [24,25]. Such balance between carbon inflow and outflow determines the amount of C stored the soil. The C balance of cultivated ecosystems depends largely on management practices [62, 65]. The extent of SOC loss related to the conversion of native forests to pasturelands needs to be understood well to develop the GHG mitigation strategies of tropical livestock production systems. In this study, we evaluated the degree of SOC depletion related to the conversion of native forest ecosystems to extensive pasturelands in Mexico with the hypothesis that the SOC stock reduction is significant. As this phenomenon implies, there is a strong need to look for environmental friendly livestock production alternatives at both local and regional scales, which would contribute to reducing soil CO_2 emissions. Recent studies have suggested that carbon sequestration and storage in grassland vegetation and soils are effective strategies to mitigate CO_2 emissions [26,27]. Tropical agroforestry systems, including silvopastoral systems (SSPs), have been recognized as a potential means for capturing and storing large amounts of carbon in biomass and soils compared to pasture

monoculture [28]. In this regard, we also reviewed and discussed the different soil organic carbon enhancement strategies in tropical pasturelands.

2. Materials and Methods

2.1. Literature Search and Collection of Relevant Information

We searched the published research reports related to the changes in SOC stocks from the conversion of native forest ecosystems to pasturelands. We used the Web of Science, Google Scholar, and CONRICYT (National Consortium of Resources on Scientific and Technological Information, Mexico) search engines to explore research papers published in peer-reviewed journals and registered books. To search the literature, we used keywords like carbon loss, soil organic carbon, land use change, forest conversion, pastureland establishment, carbon pools, carbon stocks, and carbon depletion. We used both English and Spanish terms for each them. For the purpose of analysis, we delimitated our search to only field studies carried out within Mexican territory. We developed a database of the studies that simultaneously report SOC stocks between native forests and pasturelands. The analysis considered only those studies with paired measurements of SOC content of primary vegetation and nearby pastures. The dataset contained 66 observations with paired measurements of SOC content between native forests and pasturelands presented in 23 research papers published during the period of 1994 to 2017 (Supplementary Table S1). This means that there were 66 measurements from primary vegetation plus 66 corresponding, paired measurements from pastures. Since our focus was to evaluate the SOC difference between native forests and pasturelands, we carefully ensured that the corresponding data were part of the same research and were conducted simultaneously for each of the observations. Out of 66 paired observations, we found 11 observations for dry tropical forests [29–35], 13 observations for humid tropical forests [34,36–42], 18 for highland forests [34,36,43–49], 11 for tropical scrubs and rangelands [34,50,51], and 13 for tropical mangrove forests [34,52]. Inland mangrove forests were converted to pasturelands, especially in southeastern Mexico during the past decades [52–54].

Dry tropical forests are the tropical deciduous and sub-deciduous forests where there is a strong seasonal variation in precipitation with a pronounced dry season. These forests are diverse in species composition, but some of the common species include *Bursera simaruba* (L.) Sarg., *Lonchocarpus constrictus* Pittier., *Piscidia piscipula* (L.) Sarg., *Jatropha gaumeri* Greenm., *Caesalpinia eriostachys* Benth., and *Cordia alliodora* (Ruiz & Pav.) Oken. Humid tropical forests are the lowland evergreen and semi-evergreen tropical forests where there are no pronounced limitations of rainfall and temperature for plant growth. Some of the common species of this type of forests include *Brosimum alicastrum* Sw., *Manilkara zapota* (L.) P. Royen, *Tabebuia rosea* (Bertol.) DC., *Thouinidium decandrum* (Bonpl.) Radlk., *Astronium graveolens* Jacq., *Cynometra oaxacana* Brandegee, and *Ficus insipida* Wild. Tropical highland forests are the upland coniferous and mixed forests where the predominant climate is temperate to mild temperate caused by higher altitudes. Different species of *Pinus* L., *Quercus* L., *Abies religiosa* (Kunth) Schitdl. & Cham., *and Cupressus lindleyi* Klotzsch ex Endl. are some of the dominant trees of these forests. Tropical scrubs and rangelands feature xerophytic vegetation and are located in arid and semi-arid regions. Tropical mangroves refer to the vegetation located along coastlines and bays of rivers, lakes, and sea. Common species of these forests include *Rhizophora mangle* L., *Avicennia germinans* (L.) L., *Laguncularia racemosa* (L.) C.F. Gaertn., and *Conocarpus erectus* L. Occasionally, such vegetation is found in inland swampy areas with deep and fine-textured soil [55]). Carbon stocks data from secondary forests were not included in the analysis because our focus was to analyze the changes from native forest ecosystems to pastureland conversion. Research papers reporting the carbon stocks from remote sensing methods without field sampling were not included in the analysis.

2.2. Historical Change in Forest and Pastureland Cover in Mexico

We compared the area covered by different forest ecosystems and grasslands for the year 1976, 1993, 2000 and 2013. The vegetation and land use map (series V) of INEGI (Mexican National Institute of Statistics and Geography) was analyzed to calculate the current land use in Mexico [56]. The land use data for the years 1976, 1993, and 2000 were respectively derived from INEGI vegetation and land use map series I and II and an updated map for the year 2000 which was already published [13]. All those maps were developed by the interpretation of Landsat Thematic Mapper (TM) satellite images and field verification. Using the 2013 INEGI data, we developed a map (Figure 1) showing the current spatial distribution of cultivated and induced pasturelands in Mexico by using ArcGIS software (ESRI, Redlands, CA, USA). Extensive livestock production activities are more concentrated on the southern and eastern part of Mexico corresponding to humid and dry tropical regions (Figure 1). The conversion of forest ecosystems for grassland establishment was extensive during the decades of 1970 and 1980 in Mexico. Cultivated and induced pastureland area increased from 149,617 km^2 to 225,135 km^2 from 1976 to 2000 (Table 1). Induced and cultivated pastureland for livestock production currently occupy 189,573 km^2 of land area in Mexico (Table 1).
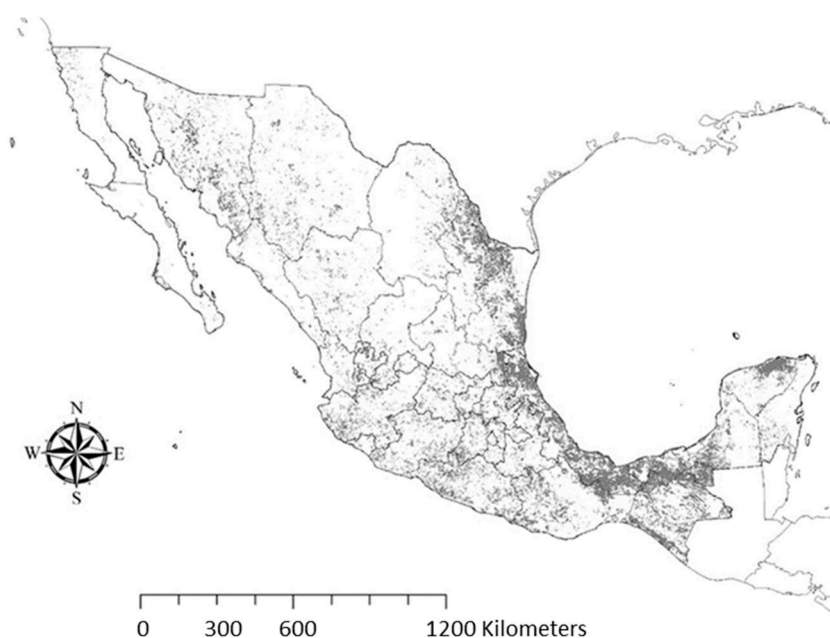
Figure 1. Distribution of cultivated and induced pastureland in Mexico (Data source: INEGI 2013). Black patches represent pastureland cover. The expansion of livestock production is high in southeast of Mexico.

Table 1. Historical change in forest and grassland cover (square kilometers) in Mexico.

Principal Land Use/Land Cover	1976 (km^2) [a]	1993 (km^2) [a]	2000 (km^2) [a]	2013 (km^2) [b]
Highland forests	352,049	347,084	331,236	345,721.49
Humid and dry tropical forests	377,598	352,798	314,340	357,620.53
Scrublands	607,472	572,118	560,791	598,883.43
Grasslands	254,396	268,700	311,375	272,050.63
Natural	104,779	94,947	86,240	82,477.32
Cultivated and induced	149,617	173,753	225,135	189,573.31
Annual and perennial cropland	262,389	290,325	325,057	325,967.30
Wetland	22,941	22,223	18,887	10,457.18

[a] Mexican National Institute of Statistics and Geography (INEGI) vegetation and land use map first, and second series, and updated map for the year 2000 [13], [b] INEGI vegetation and land use map fifth series, analyzed for this study.

2.3. Soil Organic Carbon Pool and Changes

We used a meta-analysis procedure of data synthesis and conversion [57,58]. Soil organic carbon stocks were normally reported as the amount per unit of land area (Mg C ha^{-1}), however, there were nine studies reporting SOC as a fraction of soil (percentage of sample weight). In the cases where SOC content was reported as the fraction of soil sample, we used the respective bulk density data (BD) from the same study and reported soil depth to calculate SOC stocks (Mg C ha^{-1}) by using Equation (1). We considered the BD values of similar soil type for those studies which did not report soil BD [59].

$$\text{SOC stocks (Mg C ha}^{-1}) = \text{BD (D} \times 10{,}000) \times (\text{SOCF}/100) \tag{1}$$

where BD is the soil bulk density (g cm^{-3}), D is the soil depth (m), and SOCF is the soil organic carbon fraction (percentage).

The total SOC difference in percentage (relative loss) was considered to be an indicator of SOC loss associated with land conversion and was calculated by using Equation (2).

$$\text{Relative SOC loss (\%)} = [(\text{SOC forest} - \text{SOC pasture})/\text{SOC forest}] \times 100 \tag{2}$$

The relative SOC loss refers to the total difference in soil organic carbon stocks between a native forest ecosystem and pastureland and is expressed as the percentage of original stocks. The respective CO_2 equivalent emissions from soil organic carbon depletion were calculated as the amount of carbon in the oxidized form using respective molecular weights (CO_2 eq. $= C \times 44/12$). We used the absolute SOC loss values for respective native forest ecosystems to quantify the megagrams of CO_2 equivalent emission per hectare.

2.4. Data Analysis

The carbon stocks data of native forests were classified into five principal native ecosystem types found in Mexico: dry tropical forests (DTF), humid tropical forests (HTF), highland forests (HLF), tropical mangrove (TMG), and tropical scrubs and rangelands (TSR). Soil depths were categorized into 0–30 cm, 30–60 cm, and >60 cm. All the studies reporting SOC up to 30 cm or below were categorized to the 0–30 cm group, the studies reporting SOC between 30 to 60 cm were categorized to the 30–60 cm group, and those reporting to more than 60 cm depth were categorized into the >60 cm group.

To analyze the data, we performed a generalized linear mixed model (GLMM) fit by maximum likelihood (Laplace approximation) with the following formula (Equation (3)).

$$\begin{aligned}\text{Model} = \text{glmer(SOC \textasciitilde LandUses} \times \text{CategoriesD} + (1|\text{Study}),\\ \text{family} = \text{Gamma(link = "inverse"), data = Database)}\end{aligned} \tag{3}$$

where LandUses denote pasture or forest, CategoriesD denote soil depth categories: 0–30, 30–60, and >60 cm and Study denoted the published research from where we obtained the data.

After the GLMM, we performed a general linear hypothesis (GLH) to compare multiple factors, similar to a Tukey Honest Significance Difference (HSD) analysis. For this, we used the following formula (Equation (4)).

$$\text{glht(Model, linfct = mcp(LanCat = "Tukey"))} \tag{4}$$

where LanCat was the interaction between land use (LandUses) and soil depth categories (CategoriesD).

To evaluate the effect of land use change by native forest type, another GLMM analysis was carried out with the following formula (Equation (5)).

$$\begin{aligned}\text{Model} = \text{glmer(SOC \textasciitilde LandUses} \times \text{Ecosystems} + (1|\text{Study}),\\ \text{family} = \text{Gamma(link = "inverse"), data = Database)}\end{aligned} \tag{5}$$

where LandUses denotes pasture or forest, Ecosystems denotes the original native forest type, and Study denotes the published research from where we obtained the data.

The GLMM and GLH were done with packages lme4 [60] and multcomp [61] in R [62].

3. Results

3.1. Soil Organic Carbon Loss from Land Use Change

We found that the reported soil depth and SOC difference between native forest ecosystems and pastureland varied strongly among studies. Six out of 66 studies reported an increase in SOC stock in pastureland compared to native forests, while 60 studies reported a loss of SOC. The highest relative loss (85.4%) was reported in tropical mangrove forests to a soil depth of 50–100 cm in the state of Tabasco, southern Mexico, while the minimum loss (0%) was reported in the tropical thorn scrubs of Sonora, northern Mexico (Supplementary Table S1). Among the studies reporting an increase in SOC stock, the highest relative increase (55%) was reported in humid tropical forests to 0–20 cm depth in the state of Veracruz (Supplementary Table S1).

The analysis showed that soil organic carbon stocks were significantly lower in pasturelands compared to native forests (Figure 2). The median concentration of SOC in native forests up to 30 cm depth was 59.6 Mg ha^{-1} compared to 28.6 Mg ha^{-1} in pasturelands. This is equivalent to a 52% reduction of SOC stock to this soil horizon. Up to 60 cm depth, the median SOC stock was 98.2 Mg ha^{-1} in native forests, while that in pasturelands was 67.2 Mg ha^{-1}. This difference is equivalent to a 31.6% reduction in SOC stock (relative loss) in this horizon. The median SOC difference in the deeper soil horizon (>60 cm) was 40.6% (Figure 2).
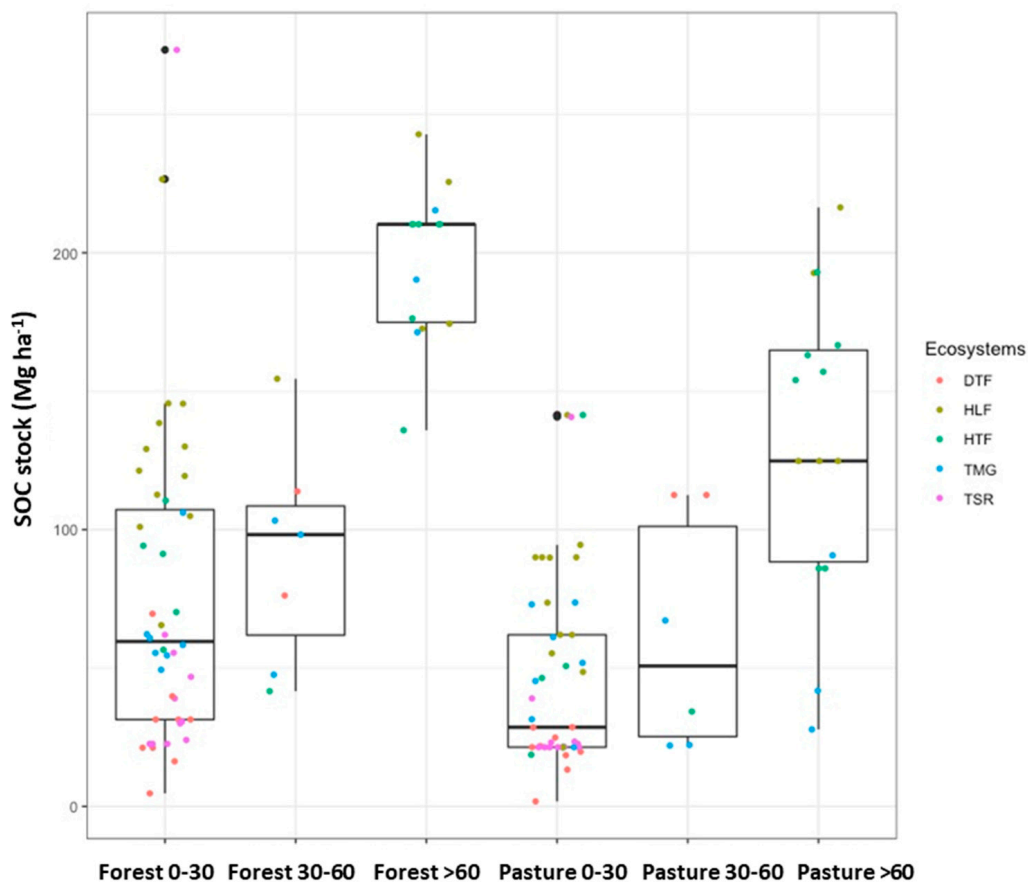
Figure 2. Soil organic carbon stocks between native forests and pastureland by reported depth categories. The native ecosystem types are denoted as follows. DTF: dry tropical forests; HLF: highland forests; HTF: humid tropical forests; TMG: tropical mangroves; TSR: tropical scrubs and rangelands.

A generalized linear mixed effect model showed that land use change from native forests to pastureland significantly affected the SOC carbon stocks (model intercept = 0.0222 ± 0.004, $p < 0.001$). Soil depth also showed a significant effect on the SOC stock difference (Table 2). The model also showed that there was a significant interaction between land uses (forest vs. pasture) and soil depth (Table 2).

Table 2. Coefficients and level of significance obtained from generalized linear mixed effect model (GLMM) for soil organic carbon (SOC) as a function of land use, soil depth, and studies, where we considered pasture as the reference level of land use type. CategoriesD: Soil depth categories (0–30, 30–60 and >60 cm); LandUses: land use (forests vsersus pasture).

	Estimate	Std. Error	*t* Value	Pr(>|z|)	Significance [1]
(Intercept)	0.0222	0.0040	5.5229	<0.001	***
LandUses Pasture	0.0064	0.0015	4.2810	<0.001	***
CategoriesD30–60	0.0003	0.0032	0.1067	0.915	
CategoriesD > 60	−0.0084	0.0025	−3.3496	<0.001	***
LandUsesPasture:CategoriesD30–60	−0.0032	0.0037	−0.8480	0.396	
LandUsesPasture:CategoriesD > 60	−0.0038	0.0018	−2.0919	0.036	*

[1] Significance code: $p < 0.05$ = *, $p \leq 0.01$ = **, $p \leq 0.001$ = ***.

By a general linear hypothesis analysis, we showed the significant differences between the SOC of forests and pastureland at different depth intervals (Table 3). The difference between the SOC stocks of forests and pastureland was highly significant at 0–30 cm depth and non-significant at 30–60 cm and >60 cm depths (Table 3).

Table 3. Analysis of general linear hypotheses (GLHs) to compare the significant differences between multiple factors.

Factors	*p* Value	Significance [1]	Logical Relation [2]
Pasture 0–30 versus Forest 0–30	<0.001	***	Yes
Forest 30–60 versus Forest 0–30	0.999		Yes
Pasture 30–60 versus Forest 0–30	0.925		No
Forest >60 versus Forest 0–30	0.008	***	Yes
Pasture >60 versus Forest 0–30	0.181		No
Forest 30–60 versus Pasture 0–30	0.366		No
Pasture 30–60 versus Pasture 0–30	0.972		Yes
Forest >60 versus Pasture 0–30	<0.001	***	No
Pasture >60–Pasture 0–30	<0.001	***	Yes
Pasture 30–60 versus Forest 30–60	0.920		No
Forest >60 versus Forest 30–60	0.048	*	Yes
Pasture >60 versus Forest 30–60	0.341		No
Forest >60 versus Pasture 30–60	0.011	*	No
Pasture >60 versus Pasture 30–60	0.100		Yes
Pasture >60 versus Forest >60	0.091		Yes

[1] Significance code: $p < 0.05$ = *, $p \leq 0.01$ = **, $p \leq 0.001$ = ***. [2] The interactions considered relevant (Yes) among all possible interactions.

Another GLMM analysis also showed a significant effect of land use (forests vs. pasture) on the difference in SOC stocks between forests and pasturelands (Table 4). Forest types showed significant influence on the model except for tropical scrub and rangelands (TSR). However, the model showed that there was no significant interaction between land use (forest vs. pasture) and forest types (Table 4).

Table 4. Coefficients and level of significance obtained from the generalized linear mixed effect model (GLMM) for SOC as a function of land use, native forest types, and studies, where we considered pasture as the reference level of land use type. Ecosystems: native forests; DTF: dry tropical forests; HLF: highland forest; HTF: humid tropical forests; TMG: tropical mangrove; TSR: tropical scrub and rangelands, LandUses = land uses (Forest versus pasture).

	Estimate	Std. Error	*t* Value	Pr(>|z|)	Significance [1]
(Intercept)	0.03024	0.00533	5.67421	<0.001	***
LandUses Pasture	0.00217	0.00401	0.54281	0.587	
Ecosystems HLF	−0.01704	0.00568	−2.99860	0.002	**
Ecosystems HTF	−0.01446	0.00586	−2.46756	0.013	*
Ecosystems TMG	−0.01887	0.00708	−2.66579	0.007	**
Ecosystems TSR	−0.00262	0.00682	−0.38423	0.700	
LandUses Pasture:Ecosystems HLF	0.00132	0.00418	0.31663	0.751	
LandUses Pasture:Ecosystems HTF	0.00002	0.00422	0.00427	0.996	
LandUses Pasture:Ecosystems TMG	0.00819	0.00487	1.68164	0.092	
LandUses Pasture:Ecosystems TSR	0.00663	0.00566	1.17103	0.241	

[1] Significance code: $p < 0.05$ = *, $p \leq 0.01$ = **, $p \leq 0.001$ = ***.

3.2. CO_2 Equivalent Emissions Related to Land Conversion

The median CO_2 equivalent emissions from the loss of SOC due to the conversion of native forests to pastureland land ranged from 46.7 Mg CO_2 eq. ha^{-1} to 165 Mg CO_2 eq. ha^{-1} depending upon the type of the original native ecosystems (Figure 3). The highest loss was observed in tropical mangrove forests and the lowest in dry tropical forests. The loss of SOC from tropical mangrove forests varied greatly among sites resulting in a higher error level (Figure 3).
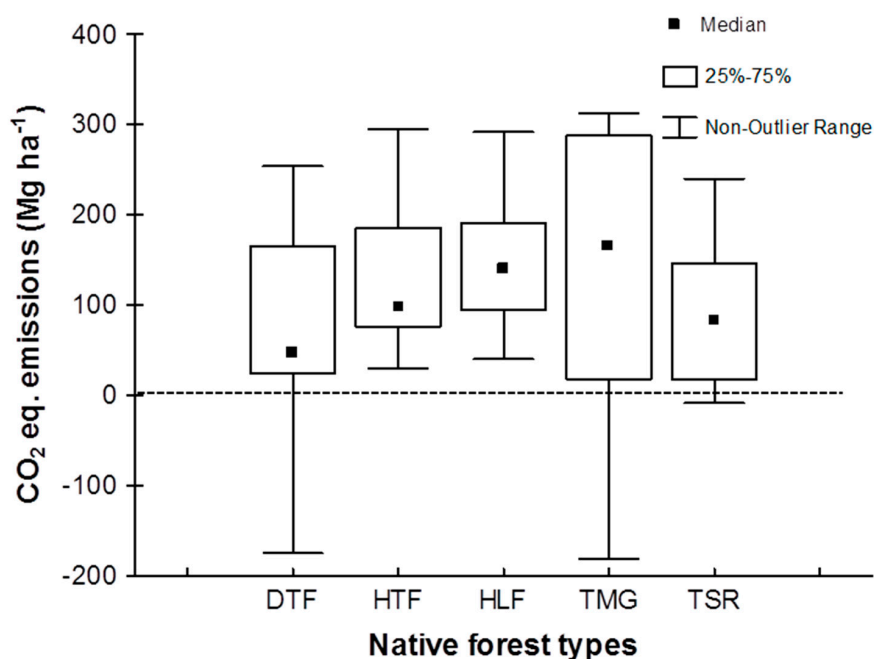
Figure 3. CO_2 equivalent emissions (Mg ha^{-1}) related to soil organic carbon depletion from forest to pastureland conversion in Mexico. DTF: dry tropical forests; HTF: humid tropical forests; HLF: highland forests; TMG: tropical mangroves; and TSR: tropical scrubs and rangelands.

4. Discussion

4.1. Soil Organic Carbon Loss

Our results indicated that land conversion from the native forests to the cultivated or induced pasturelands significantly reduced the SOC stocks in Mexico, owing to the subsequent increased

mineralization, leaching, and soil erosion caused by the land use change. Land conversion from forests to pasturelands alter the physical, biological, and chemical properties of soil as a result of grazing, burning, and changes in plant species composition [11,12,44,50,63,64]. Such conversions may change the rate of inflow and outflow of organic carbon as well as other nutrients [12,58,65]. Sixty out of 66 observations reported a decrease in SOC from forest to pastureland conversion, while six studies reported an increase [36,40,51,52]. The increase in soil bulk density and the original differences in soil type could explain the increased SOC stocks in those studies. The loss of 31% to 52% SOC in this analysis represents a large quantity of CO_2 emissions associated with land conversion from forests to pasturelands. The average loss of SOC across all ecosystems in our analysis was 106.9 Mg CO_2 eq. ha^{-1}. The total increase in cultivated pastureland area between 1976 and 2013 in Mexico was 3.996 million hectares. If we multiply this value with the average CO_2 eq. emission rate, we obtain 427.3 Tg CO_2 eq. historical emissions of SOC as the legacy of livestock production-related land conversion in Mexico during the last 37 years. Carbon loss from the conversion of tropical scrubs and rangelands to pastureland was lower compared to the loss from the conversion of mangrove forests, highland forests, and humid tropical forests. These high carbon density forests were primarily distributed to the southern part of Mexico where livestock production is currently increasing [66–68]. Tropical mangroves are considered to be one of the high carbon density forest ecosystems and we found that such ecosystems were also converted to pasturelands in southeastern Mexico [52–54].

A 31% to 52% loss of SOC from forests to pasturelands conversion in Mexico is smaller than previously documented by Lal (2004) [11], who reported that the SOC depletion from the conversion of native ecosystems to cultivated ecosystems reaches up to 60–75% in the tropics. However, our results are similar to those of Smith et al. (2016) [16], who estimated a loss of 40% to 63% SOC from the conversion of global tropical forests to pasturelands using the dynamic global vegetation model (DGVM). In Colombian Amazonia, the SOC stocks (0–30 cm depth) were 20% to 28% lower in highly grazed (2.7 heads of forage-fed livestock per hectare) tropical pasturelands compared to primary forests (47.1 Mg C ha^{-1}) [12]. A recent review reported that extensive grazing decreased belowground carbon in grassland ecosystems by 21.6%, with the largest decreases in microbial biomass [58].

In the Brazilian Cerrado, SOC content in pastureland was reported to be similar to that of natural forests, but slightly higher SOC stocks were observed in the pastureland due to increased soil bulk density [69]. The increase in soil organic carbon contradicted with our results, where we found up to a 52% reduction in SOC stocks from natural forests to pastureland conversion. The increase in SOC stocks in pastureland was explained by the increase in soil bulk density rather than the real increase in carbon content in the Brazilian Amazon [70]. The increase in bulk density was the result of soil trampling caused by cattle grazing. The combined effect of repeated fires and intensive cattle grazing in pasture monoculture severely reduced the soil organic carbon and ultimately the long-term land productivity in the Pacific coast of Mexico, one of the studies we included in this analysis [30]. Soil organic carbon from C3 plants origin decreased significantly with a slight increase in soil organic carbon from C4 plants origin after 11 years of land conversion from forests to pastureland in this region [30].

4.2. Management Recommendations for Carbon Stock Enhancement in Tropical Grasslands

Since the extension of grassland is increasing, proper management is necessary to mitigate SOC losses [71,72]. Management practices like the establishment of agroforestry systems that combine grasses with shrubs and trees increase SOC stocks, in addition to providing potential increases in the nutritional value of animal forage and other opportunities to provide resources such as human food, wood, and fuelwood [17,26,73]. There are studies demonstrating that agroforestry practices can significantly increase biomass and soil carbon storage in livestock systems [28,74]. Live fences, fodder banks, scattered trees on pasturelands, and tree plantation at higher densities are some examples of common silvopastoral systems that increase carbon sequestration [17,66,75,76]. Sparing part of the land area for forest plantation also increases carbon stocks within the livestock production units [77]. In

Chilean Patagonia, the net SOC input was 0.15 Mg C ha^{-1} year^{-1} in a silvopastoral system compared to 0.09 Mg C ha^{-1} year^{-1} in treeless grazing lands [78]. In the humid tropics of India, litterfall added 1.6 Mg C ha^{-1} year^{-1} in a coconut-based silvopastoral system compared to 0.3 Mg C ha^{-1} year^{-1} in open pasture [79]. In Chilean Patagonia, total carbon storage including SOC (0–40 cm depth) and biomass was 224 Mg C ha^{-1} in silvopastoral systems compared to 177 Mg C ha^{-1} in managed prairie pasturelands [78]. In Central Matalagalpa, Nicaragua, SOC content (0–10 cm) in the silvopastoral systems under the trees of *Guazuma ulmifolia* Lam., *Tabebuia rosea* Bertol., *Albizia saman* Jacq., and *Enterolobium cyclocarpum* (Jacq.) Griseb. was 7.33 mg g^{-1} higher than open grasslands [80]. In Guanacaste, Costa Rica, SOC stocks (0–60 cm) increased up to 43% after four years of inclusion of leguminous trees in tropical pasturelands [81,82]. In Colombia, intensive silvopastoral systems of *Leucaena leucocephala* (Lamb.) de Wit. (>10,000 plants ha^{-1}) produced up to 47% more biomass than treeless pastures and added 3 Mg of dry matter ha^{-1} year^{-1} from tree pruning, which rapidly incorporated into the soil enhancing SOC stocks [17]. In Florida, USA, the total ecosystem carbon stock, including SOC (0–30 cm), in a silvopastoral system was 144 Mg C ha^{-1} compared to 83 Mg C ha^{-1} in improved subtropical pasturelands [83].

Identifying appropriate spacing between tree lines in a silvopastoral system is also an important management aspect for soil organic carbon enhancement. In Tabasco, Mexico, SOC content was 34 g kg^{-1} to a distance of 3–6 m from live fences of *Glicidia. sepium* (Jacq.) Walp. compared to 26 g kg^{-1} at the distance of 6–9 m from the live fence in tropical pastureland of *Brachiaria decumbens* Stapf [73]. The diurnal and seasonal variation in soil temperature, soil moisture, and soil respiration were lower in a silvopastoral system with live fences of *G. sepium* compared to pasture monoculture in those sites [19].

Other management practices like rotational grazing, maintaining appropriate grazing intensity, controlling soil erosion, and the avoidance of biomass burning also increase the aboveground as well as belowground carbon stocks in tropical pasturelands [26]. In a global review, it is reported that grassland management practices, such as irrigation, earthworm introduction, planting improved grass species, legume introduction, grazing improvement, and fertilization can sequester up to 0.54 Mg C ha^{-1} year^{-1} of SOC in pasturelands [84]. Grazing intensity affects SOC because above- and belowground carbon input is reduced in overgrazed pastures [63]. In Colombian Amazon, SOC stock (0–30 cm) was 68.8 Mg C ha^{-1} in a low-grazed pasture compared to 37.9 Mg C ha^{-1} in a 20-year-old high-grazed pasture [12]. Carbon stock in moderately grazed pasture was 22% higher than permanently overgrazed pasture (<1 ha of land animal unit^{-1} year^{-1}) in a semi-arid grassland of Jalisco, Mexico [85]. Soil compaction from animal trampling reduces the ultimate mixing of soil organic matter into lower soil horizons and leads to higher decomposition of exposed surface organic matter, which in turn, reduces the soil organic carbon stocks. Compaction of subsoil also fosters soil erosion and runoff resulting in the loss of SOC and other nutrients [16]. In a global meta-analysis, the rate of carbon flux from soil respiration was 4.3% higher in grazed pasturelands compared to non-grazed ones [58]. Rotational grazing with sufficient recovery time could reduce the impact of overgrazing and enhance SOC in tropical grazing lands. Grazing intensity also alters the soil microbial activity and microbial biomass. Soil microbial biomass was significantly lower in a high-grazed pasture compared to a low-grazed one in Los Tuxtlas Veracruz, Mexico [41].

In addition to different agroforestry arrangements and grassland management practices, use of forest management practices on spare land (like planting trees on riparian areas, along the corridors and pastureland margins, and contour planting on the slope lands) within the farm unit can significantly increase the carbon stocks of tropical livestock systems [77,86]. Carbon sequestration in tropical pasturelands can significantly offset non-CO$_2$ GHG emissions linked to livestock production, which seems urgent to achieve the 2 °C global warming target limit as accorded in the Paris Agreement [87].

5. Conclusions

The area of extensive grasslands for bovine livestock farming is increasing in Mexico. The loss of soil organic carbon stocks from the conversion of native forest ecosystems to grasslands is significant and reaffirms the findings reported in other parts of the tropics. The role of silvopastoral systems in soil organic carbon stock enhancement is well acknowledged in many parts of the tropics and sub-tropics. Hence, the adoption of such agroforestry systems could be an important management strategy to reduce SOC loss in Mexican grasslands. The role of tropical livestock production systems and their management needs further attention in research and greenhouse gas mitigation strategies.

Supplementary Materials: The following are available online at http://www.mdpi.com/2077-0472/8/11/181/s1, Table S1: Reported soil organic carbon stocks and their differences between native forests and pasturelands in Mexico.

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