Article

Assessment of the Interrelationships of Soil Nutrient Balances with the Agricultural Soil Emissions and Food Production

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Abstract: Sustainable and adjusted soil management practices are crucial for soil quality, namely in terms of the nutrient budget. On the other hand, soil characteristics are interlinked with agricultural sustainability and food supply. In other words, soil quality influences agricultural performance and food chains, but it is also impacted by agricultural activities. In this context, this research aims to evaluate the spatial correlations of the soil nutrient balance around the world and analyse how this variable is interrelated with agricultural soil emissions, agricultural output, and food supply. To achieve these goals, data from the FAOSTAT database were considered. This statistical information was analysed with spatial autocorrelation approaches to identify spatial clusters around the world that can be considered as a basis for designing common policies. To perform panel data regressions to identify marginal effects between variables, data were first evaluated using correlation matrices and factor analysis. The results highlight that there is space for common strategies worldwide to preserve soil quality, as in some parts of the world the problems are similar. In these frameworks, the international organizations may have a determinant contribution.

Keywords: spatial autocorrelation; matrices of correlation; factor analysis; panel data regressions

1. Introduction

Information about land characteristics is an important factor in integrated soil management and here, beyond the scientific contributions [1], knowledge of local populations about the soil properties provides relevant contributions [2]. Adjusted management plans may make local needs compatible with soil quality conservation [3], where agricultural practices determine the results obtained [4] in terms of sustainability, along with the farming systems adopted [5] and the crops species [6]. Sustainable practices differ for each agricultural activity and also between countries and regions [7].

Different tillage, fertilisation techniques and rotation approaches are agronomic practices that may make a difference in the quality of the soil [8], in rice-wheat systems for example. Soil conservation techniques are often interrelated with water management approaches [9], because the dynamics of these two resources (soil and water) are mutually dependent [10]. Soil quality also impacts the characteristics of the crops obtained [11] and the health of animal activities [12].

To promote sustainable and best management practices in the agricultural sector, with benefits for the environment and soil quality, farmers need to be supported with technical knowledge, and in these conditions, extension services are crucial [13], as well as training programs to increase the technical skills of stakeholders related with the farming activities.

The agricultural institutions (national and international), organizations (cooperatives and associations, for example) and policies (Common Agricultural Policy in European Union, for instance) are crucial in order to achieve sustainable development goals [14].

The new challenges created by the world population growth and the needs of dealing with the climate change contexts call for alternative ways of better managing the available resources [15], specifically in contexts of agricultural intensification [16] and soil erosion [17]. In these frameworks, the agricultural activities are sources and sinks of greenhouse gases, where the soil carbon sequestration is fundamental for the sustainability [18]. The soil degradation and erosion are threats that particularly concern the several society stakeholders [19].

Considering these issues of the soil management and its interrelationships with the several dimensions of the agricultural sector, this study intends to analyse the soil nutrient balance worldwide through spatial assessments to identify clusters between the countries. These analyses will be a basis for the design of joint policies and combining efforts for together solve common problems related with the soil quality. In addition, this research aims to assess the main interlinkages between the soil nutrient budget and the soil emissions and the food supply.

2. Literature Survey

Agricultural soils are impacted by the agronomic practices adopted by the farmers, where the tillage, for example, has its influence in the physical properties [20] and quality [21]. Hence, this must be considered by several stakeholders, particularly farmers and policymakers. Conventional tillage may reduce the soil organic matter and increase the carbon dioxide (CO_2) emissions [22] by soil respiration. Minimum tillage is suggested to achieve the compromise among the agricultural productions loss and the soil preservation [23]. Specifically, soil erosion is comparable to the water erosion [24]. Soil and water dynamics are correlated [25], wherein the formation of the organic matter is a complex process dependent from diverse drivers [26], such as soil temperature and humidity and carbon/nitrogen ratio of the manures.

Other farming practices have their impacts on the soil characteristics and composition, such as compost or manure application (with benefits for the agricultural activities, but with changes in the microbial community) [27], organic/conventional productions [28], organic/inorganic fertilisers [29], pasture in rotation [30], agrochemicals (affects the bacterial diversity [31], for instance) [32], plastic mulching [33], land use changes [34], straw return [35], soil fumigation [36], harvest practices [37], forest-agriculture conversion [38], conventional practices [39], field fallow [40], polymers use [41] and cover crops [42].

The soil quality is influenced by several factors, some of them from extreme phenomena [43] and the climate changes [44], nonetheless the various dimensions associated with the farming contexts explain a part of the sources of problems that bring degradation of the land, specifically those associated with salinity [45].

Soil is a key factor of production for the agricultural sector [46] and food supply [47], however, it is under pressures by the economic activities [48]. A permanent assessment of the soil quality (mainly the soil physical properties [49]) through new techniques [50], approaches [51] and technologies [52] is crucial for an adjusted soil management [53]. Namely, to maintain the levels of carbon and nitrogen through conservation practices [54] and preserve the human health [55] from toxic contaminants [56], including phthalate esters [57], heavy metals (with impacts on food safety [58]) [59] and copper balance [60]. For these evaluations, the availability of information [61] worldwide [62] is fundamental. The assessment of soil quality is also important to support strategy proposals [63] and characteristics prediction [64] under the global warming challenges [65].

The agricultural soil management is responsible for greenhouse gas emission [66], with several environmental impacts originating in the following gases: nitrous oxide (N_2O) [67] by nitrification and denitrification processes, methane (CH_4) by anaerobic conditions and CO_2 by aerobic or anaerobic environment. These greenhouse gas emissions are particularly influenced by soil type, climate, water management and composition of organic matter [68]. Hence, the agricultural soil management is interrelated with the agricultural practices and environmental impacts [69]. Thus, the interlinkages have impacts, for example, on the ecosystems services [70], soil biodiversity [71] and humus composition [72]. For example, the use of biochar into the soil may be an interesting alternative to reduce the environmental impacts and mitigate the climate change consequences [73]. Additionally, adjusted soil management may prevent soilborne diseases [74] and increase the soil organic carbon [75].

For a sustainable agricultural soil management, the agricultural policies and institutions are called to play relevant roles [76] to promote soil conservation practices [77]. This issue is particularly important in the European Union contexts, under the framework of the Common Agricultural Policy (CAP) [14], and to deal with problematic cases created by the post-Second World War contexts [78]. The public policies are specifically important in the cases where the negative impacts are self-reinforced or have dynamics of rebound effects [79].

3. Materials and Methods

To achieve the objectives proposed and considering the several relationships associated with the soil properties highlighted in the literature review, statistical information for the following variables was obtained from the FAOSTAT [80] database: agricultural soil emissions (CO_2eq, namely N_2O emissions.) in kilotonnes per ha of cropland; average value of food production (constant 2004–2006 I\$ (international dollar, an international dollar would buy in a country a comparable amount of products a U.S. dollar would buy in the United States [81])/cap, 3-year average); gross agricultural production value per ha (constant 2014–2016, 1000 I\$ per ha of cropland); and cropland nutrient flow per unit area (kg per ha). These variables were selected to represent the characteristics of the soil and their different interlinkages, namely those related with the environment, agricultural production, and food supply. Considering the availability of data for the various variables, it was considered the period 2001–2017. To associate the average valued of food production with the other indicators, the middle year for each group of three years was considered.

These indicators were first analysed through spatial autocorrelation, to identify spatial clusters worldwide, where it may be possible to design common strategies to deal with an integrated agricultural soil management. For the spatial assessments, global and local autocorrelation approaches were considered following GeoDa procedures [82,83]. For the global spatial autocorrelation, the Moran's I statistics were used [84]. The Moran's I statistics range between −1 and 0, for negative spatial autocorrelation (the values of a variable are negatively correlated with the values of the same variable in the neighbour countries), and 0 and 1, for positive autocorrelation. For the local spatial autocorrelation, cluster maps were considered. In these maps, the clusters high-high and low-low highlight positive local spatial autocorrelation for higher and lower values, respectively. The clusters high-low and low-high represent negative spatial autocorrelation. For this spatial analysis, shapefiles from the Eurostat [85] for the world countries were used that were explored through the QGIS software [86].

After this first assessment, the variables were considered to obtain indices for the integrated agricultural soil management through factor analysis [87–91] and to find marginal effects based on panel data regressions [91–93]. To identify the best models for the panel data regressions, the Spearman correlations [94] and the Granger cause statistics [95] were carried out.
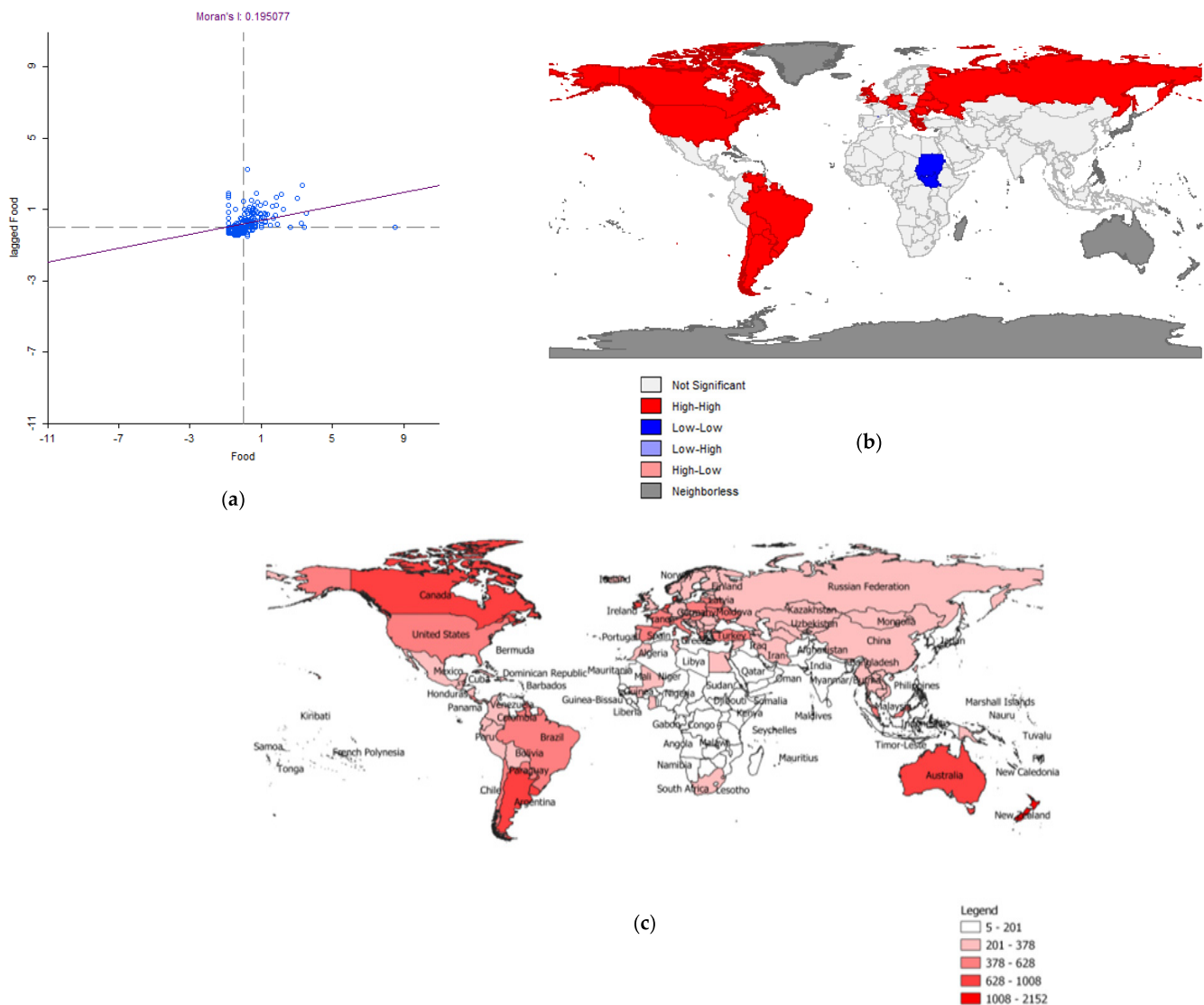
4. Spatial Autocorrelation Analysis

The spatial autocorrelation analysis reported in this section was assessed using queen contiguity matrix, for an order of contiguity of 1. Figures 1–4 show the level of global and local spatial autocorrelation and the distribution of values of the several variables considered worldwide.

(a)

(b)

(c)
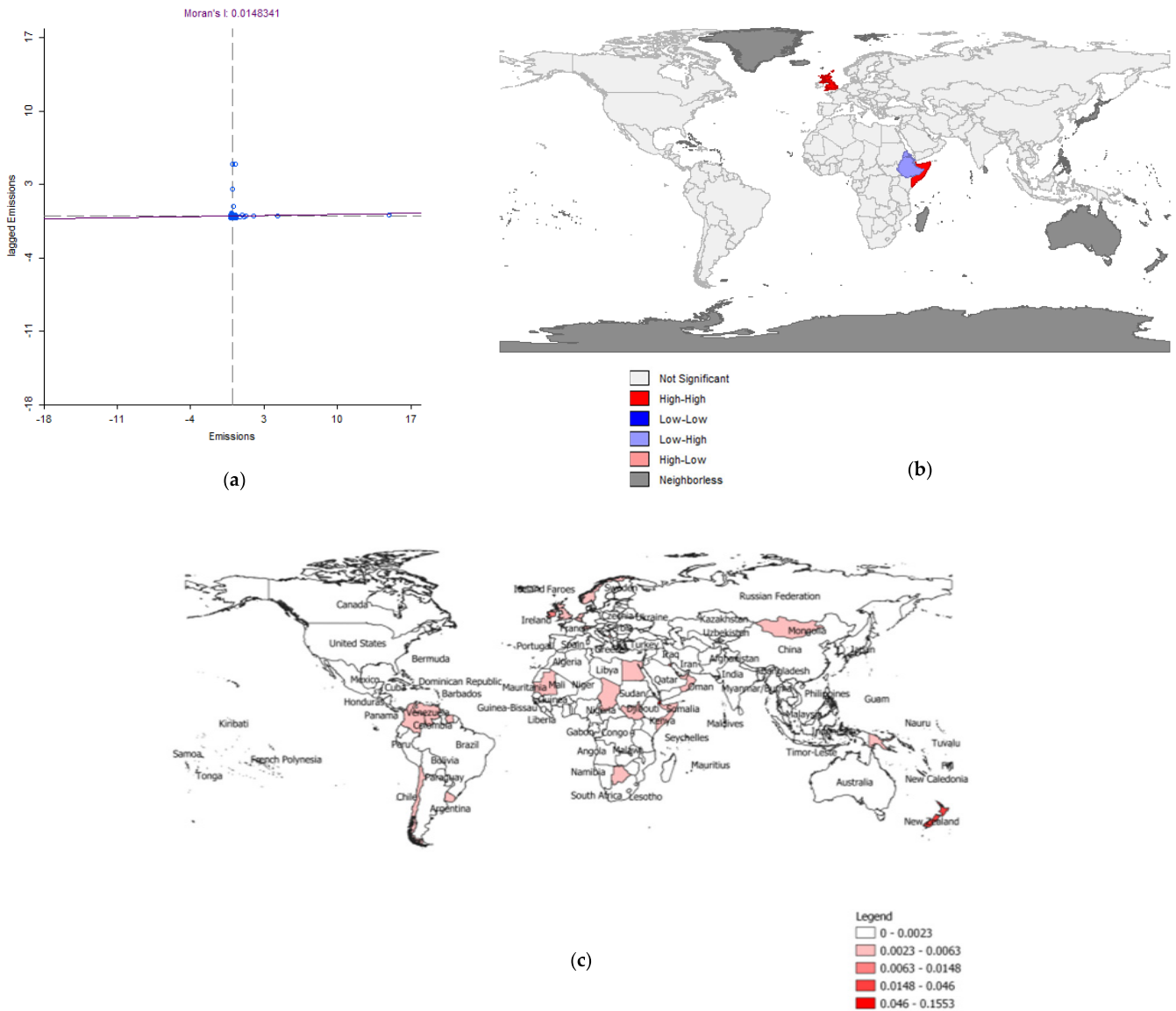
Figure 1. Global and local spatial autocorrelation and worldwide distribution for the agricultural soil emissions (CO_2eq) per ha of cropland, on average over the period 2001–2017 (kilotonnes per ha of cropland); (**a**) Global spatial autocorrelation, (**b**) Local spatial autocorrelation; (**c**) Worldwide distribution.
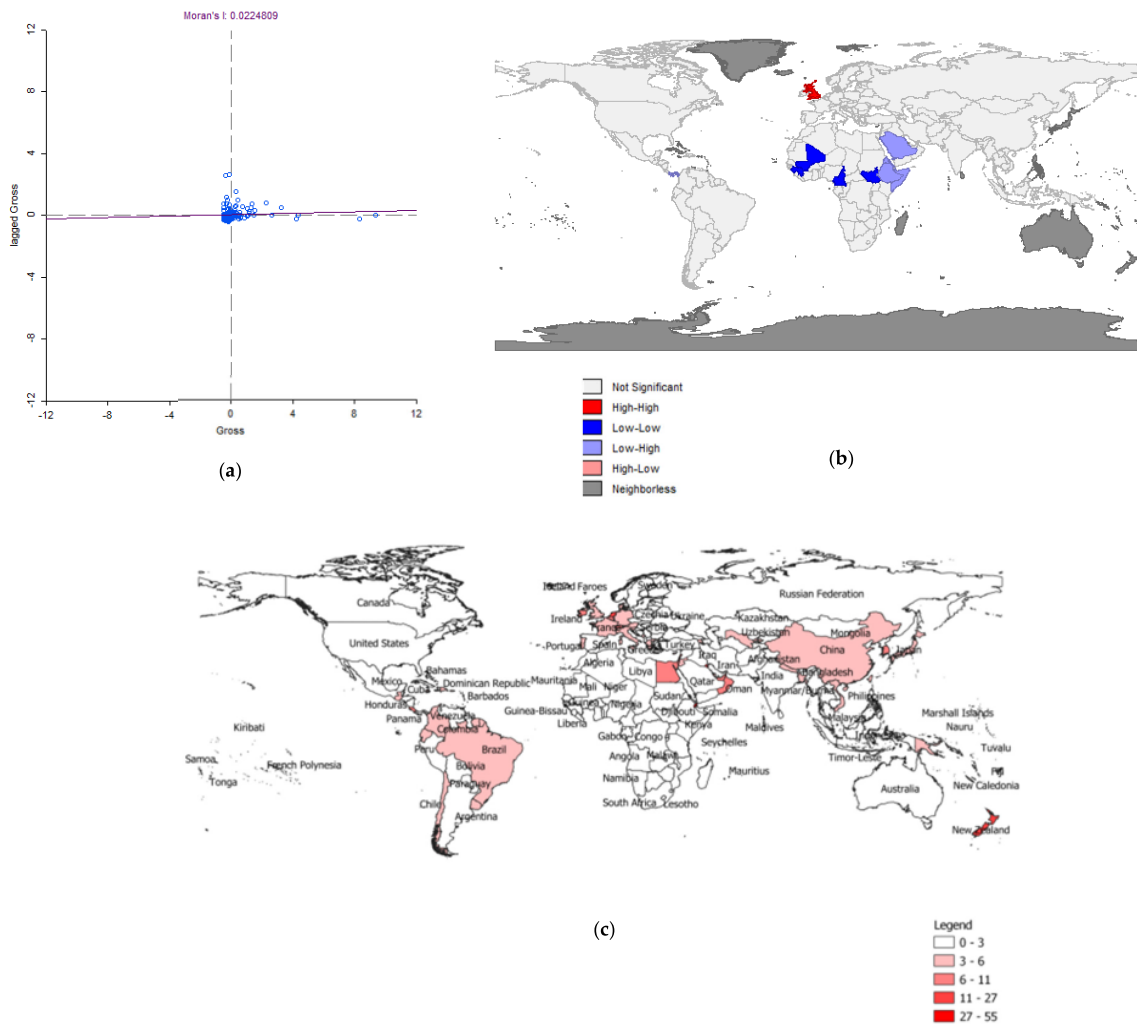
The global and local spatial autocorrelation was weak for the agricultural soil emissions (CO_2eq) per ha of cropland, and this was a consequence of values relatively low (exception for the case of New Zealand, for example) verified for this variable across the world countries (Figure 1).
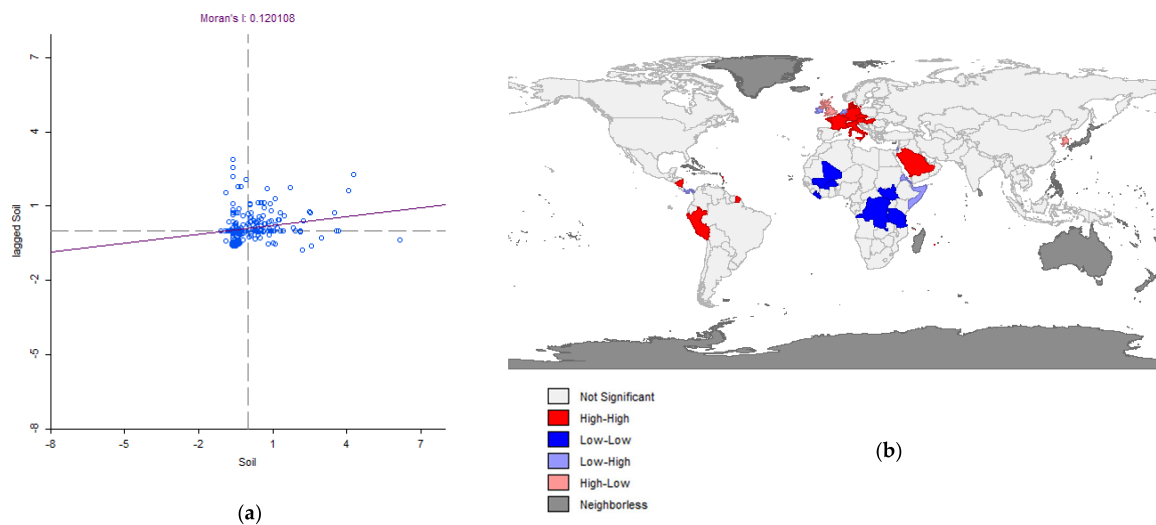
Figure 2. Global and local spatial autocorrelation and worldwide distribution for the average value of food production (constant 2004–2006 I$/cap) (3-year average), on average over the period 2001–2017 (I$ per person); (**a**) Global spatial autocorrelation, (**b**) Local spatial autocorrelation; (**c**) Worldwide distribution.

As can be observed in Figure 2, the scenario was different for the average value of food production, where there are signs of relevant positive global spatial autocorrelation and high-high local spatial autocorrelation in North and South America, Russia, and some European countries. Hence, this means that the strategies developed by the countries inside of each cluster high-high spread among neighbour countries, lead to good findings for future policies.

The gross agricultural production value per ha of cropland was, in general, low worldwide (exception for New Zealand and some European countries, for example), and this explains, at least in part, the reduced level of spatial autocorrelation for this variable (Figure 3). The cropland nutrient flow per unit area had significant signs of positive high-high local spatial autocorrelation in the European countries (Figure 4).

(**a**)

(**b**)

(**c**)

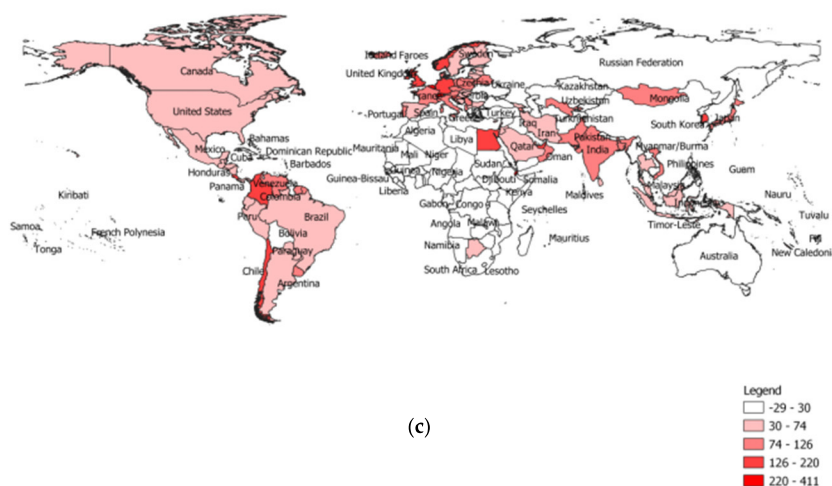**Figure 3.** Global and local spatial autocorrelation and worldwide distribution for the gross agricultural production value (constant 2014–2016 thousand I\$) per ha of cropland, on average over the period 2001–2017 (thousand I\$ per ha of crop land); (**a**) Global spatial autocorrelation, (**b**) Local spatial autocorrelation; (**c**) Worldwide distribution.

(**a**)

(**b**)

Figure 4. *Cont.*

(c)

Figure 4. Global and local spatial autocorrelation and worldwide distribution for the cropland nutrient flow per unit area, on average over the period 2001–2017 (kg per ha); (**a**) Global spatial autocorrelation, (**b**) Local spatial autocorrelation; (**c**) Worldwide distribution.

5. Identifying Indices for an Integrated Agricultural Soil Management

To facilitate the readability of the results presented here, and improve the robustness of the findings, it was obtained a balanced panel data (in which the countries and years with missing values were removed, remaining 183 countries with data for the full period of 2001–2017) and the agricultural soil emissions were converted from kilotonnes per ha into kg per ha and the gross agricultural production from 1000 I\$ per ha into I\$ per ha.

Table 1 highlights that the stronger correlations are between the agricultural soil emissions per ha, the gross agricultural production per ha and the cropland nutrient flow per ha. There was also strong correlation among the cropland nutrient flow per ha and the gross agricultural production per ha.

Table 1. Spearman's rank correlation matrix for several variables over the period 2001–2017 and across world countries.

	Agricultural Soil Emissions (kg per ha)	Average Food Production (I$ per Person)	Gross Agricultural Production (I$ per ha)	Cropland Nutrient Flow (kg per ha)
Agricultural soil emissions (kg per ha)	1.000			
Average food production (I$ per person)	0.0920 *	1.000		
	(0.000)			
Gross agricultural production (I$ per ha)	0.5996 *	0.2278 *	1.000	
	(0.000)	(0.000)		
Cropland nutrient flow (kg per ha)	0.6691 *	0.2099 *	0.6560 *	1.000
	(0.000)	(0.000)	(0.000)	

Note: *, statistically significant at 1%.

As can be observed in Table 2, it was intended to obtain an integrated agricultural soil management index, through factor analysis, with the most correlated variables. The agricultural soil emissions per ha were not considered in the factor analysis, because it was expected to contribute for the soil sustainability in a different way of the gross agricultural production and the cropland nutrient flow. Hence, the consideration of these three variables (agricultural soil emissions, gross agricultural production and cropland nutrient flow) in the index hampers the interpretation of its results. Thus, the selection of

the variables reported in this study considered the objectives proposed (analyse how soil nutrient balance is interrelated with agricultural soil emissions, agricultural output and food supply), nonetheless in future studies could be interesting to benchmark these results with those obtained considering other variables.

Table 2. Factor analysis to obtain an integrated agricultural soil management index over the period 2001–2017 and across world countries.

Method: Principal-Component Factors; Rotation: Orthogonal Varimax (Kaiser Off)				
Factor	Variance	Difference	Proportion	Cumulative
Factor1	1.668		0.834	0.834
Rotated Factor Loadings and Unique Variances				
Variable	Factor1	Uniqueness		
Gross agricultural production (I$ per ha)	0.913	0.166		
Cropland nutrient flow (kg per ha)	0.913	0.166		

Table 3 shows the top 10 countries for the integrated agricultural soil management index and highlights that the countries with higher gross agricultural production per ha, cropland nutrient flow per ha and consequent greater agricultural soil emissions per ha are not the same with better food supply per person.

Table 3. Top 10 countries for the integrated agricultural soil management index, on average over the period 2001–2017.

Countries	Agricultural Soil Emissions (kg per ha)	Average Food Production (I$ per Person)	Gross Agricultural Production (I$ per ha)	Cropland Nutrient Flow (kg per ha)	Index
Belgium	2812	473	10,261	287	3
Malta	2310	175	10,834	260	3
Switzerland	2868	304	9018	251	2
China, Taiwan Province of	1940	209	8754	224	2
Luxembourg	2503	341	4000	298	2
Egypt	3635	228	8658	220	2
United Arab Emirates	4962	100	8615	191	2
Trinidad and Tobago	2945	102	4055	257	2
Republic of Korea	1966	190	8351	173	2
Israel	1897	347	9966	114	1

Note: The country with the highest index is Djibouti, nonetheless because difficulties in validating the data it was not considered in this table.

6. Panel Data Regressions

The Granger causality tests highlight that the cropland nutrient flow per ha impacts the agricultural soil emissions per ha of cropland and the gross agricultural production per ha of cropland. Based on these findings, on the assessments carried out before and on the literature review, the results presented in Tables 4 and 5 were obtained.

Table 4. Panel data regression with the agricultural soil emissions per ha as dependent variable over the period 2001–2017 and across world countries.

Model	Prais-Winsten Regression, Correlated Panels Corrected Standard Errors (PCSEs)
Constant	−34.717 (−0.100) [0.917]
Cropland nutrient flow (kg per ha)	41.279 * (5.910) [0.000]
Pesaran's test of cross sectional independence	3.009 * [0.002]
Modified Wald test for groupwise heteroskedasticity	6.2×10^{10} * [0.000]
Wooldridge test for autocorrelation	1137.221 * [0.000]

Note: *, statistically significant at 1%.

Table 5. Panel data regression with the gross agricultural production per ha as dependent variable over the period 2001–2017 and across world countries.

Model	Prais-Winsten Regression, Correlated Panels Corrected Standard Errors (PCSEs)
Constant	1358.298 * (7.970) [0.000]
Cropland nutrient flow (kg per ha)	25.094 * (7.610) [0.000]
Pesaran's test of cross sectional independence	54.380 * [0.000]
Modified Wald test for groupwise heteroskedasticity	1.2×10^{8} * [0.000]
Wooldridge test for autocorrelation	528.496 * [0.000]

Note: *, statistically significant at 1%.

The results obtained in this study revealed the following statistical problems: cross sectional dependence, heteroscedasticity, and autocorrelation of the data sample. To deal with these frameworks, the Prais–Winsten regression, correlated panels corrected standard errors (PCSEs), following Stata [91] and Torres-Reyna [93] procedures were considered.

These findings reveal that when the cropland nutrient flow increases 1 kg/ha the agricultural soil emissions worldwide increase 41.279 kg/ha and the gross agricultural production increases 25.094 I$ per ha.

These results highlight serious problems of sustainability in the agricultural soil management worldwide because the cropland nutrient flow and the agricultural production are associated with more agricultural soil emissions, but this context is disconnected from the food supply per person.

7. Discussion

This study aimed to analyse the framework of the soil nutrient balances across the world countries and assess their interrelationships with the agricultural soil emissions and the food supply. For that, geographic information system (GIS) approaches were considered, namely, to identify evidence of spatial autocorrelations between the countries for the variables considered. Factor analysis to find indices and panel data regressions to obtain relationships among the variables were also carried out.

The literature review highlighted the impacts on the agricultural soils from the agronomic practices, where the tillage, fertilisation, rotations, and land use changes, for example, have their implications. However, the agricultural soils are also responsible by environmental impacts through the greenhouse gas emissions. Sometimes, these interrelationships create contexts with self-reinforced effects, where the agricultural policies and institutions play a determinant role to reduce the negative externalities.

The spatial autocorrelation analysis shows that the global and local spatial correlations are weak for the agricultural soil emissions, in consequence of relatively values worldwide. For the average value of food production, there are signs positive global and local spatial autocorrelation. These evidences are interesting findings for the several stakeholders, namely for the policymakers, because this means that interventions in countries positively correlated may spread for the neighbours. There are also evidences of positive spatial autocorrelation in some European countries for the cropland nutrient flow per unit area.

A correlation matrix and factor analysis reveal that there are strong correlations between the agricultural soil emissions per ha, gross agricultural production per ha and the cropland nutrient flow per ha. The agricultural soil management was interrelated with agricultural practices and has environmental impacts [66,67,69]. This means that in countries with higher, per unit of area, gross agricultural production, for example, it was expected to find greater agricultural soil emissions and cropland nutrient flow. The regressions with panel data show that there are relevant signs that is the cropland nutrient flow per ha that impacts the agricultural soil emissions per ha and the gross agricultural production per ha. The governments and international organizations may have here important contributions to design policies that encourage adjusted soil management practices that maintain the soil nutrients balances and the agricultural production without compromise the sustainability.

8. Conclusions

There is a great heterogeneity between the countries across the world; however, the clusters found from the spatial autocorrelation analysis, for the food supply and soil nutrient balances, may be relevant findings to support common strategies that promote more sustainable practices. This is particularly important when there are relevant signs that the soil nutrient balances impact the farming production and the agricultural soil emissions. In fact, when the cropland nutrient flow increases 1 kg/ha, the agricultural soil emissions rise 41.279 kg/ha and the gross agricultural production rises 25.094 I\$ per ha.

In terms of practical implications, the results obtained in this research highlight that the agricultural soil management is determinant to promote a soil nutrient balance able to maintain or increase the agricultural production to achieve the world demand for food and mitigate the agricultural soil emissions. In these contexts, it is suggested, in terms of policy recommendation, that the public, private, national, and international institutions design policies that mitigate the environmental impacts from the cropland nutrient flow.

For future research, the weak correlation between the food supply per capita, the agricultural production per ha and the soil nutrient flow per ha deserve special attention. In fact, despite the environmental impacts found for the agricultural production, this is not compensated by good indicators for food supply per capita.

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