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Research article

Outlook from the soil perspective of urban expansion and food security

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ABSTRACT

The use of soil as support for built-up areas represents only one of its several functions. Farmlands at the fringe of conurbations have more chance of being converted into built-up areas due to the favourable topography and the accessibility to existing infrastructure, being in the vicinity of urban areas. We analysed the global land-take during the period 2000–2014. The data are based on a global dataset describing the spatial evolution of human settlements using the Global Human Settlement Layer, which was derived from Landsat images collected in 1975, 1990, 2000 and 2014. Although the global land-take represents roughly 0.1% of the global terrestrial Earth, it affects 1% of the naturally fertile soils, according to the proposed Soil Productivity Indexes (SPI), based upon the potential soil productivity, calculated on the basis of the Harmonized World Soil Database. We have found that, few large conurbations develop on potentially high productive soil, while scarcely productive soils sustain the expansion of several megalopolises. On a global scale and through the centuries, considered comparatively as individual overall age of settlements, a trend between the intrinsic quality of the soils and its use for settlement purposes as major competitor, was not observed.

1. Introduction

While we are writing, more than half of it the world's population live in urban settlements (UN, 2018). Globally, by 2030 urban areas are projected to house 60 per cent of people (UN, 2014). These interrelated tendencies of global change in demography, and connected land use, are the new normal, and urbanization and food production are in competition for the soil. Agriculture is under pressure to concurrently produce enough food for a growing population while minimising impacts on the total environment (Sukhdev, 2018; UNEP, 2016). Examining the processes of human–environment interaction on evolutionary timescales as a context to better understand current challenges of sustainability a question arises, does man use the most suitable soils to produce food to build his own cities, always and everywhere? The use of soil as a physical support for human activities represents one of its possible functions; however, this type of use prevents, or reduces, many other functions. In fact, the expansion of built-up areas, and the consequent increase of impervious areas, considered here as the land take[1], can be considered among the most irreversible forms of soil degradation (Amundson et al., 2015). This prevents the soil from being available to perform agricultural activities. Past policies related to land use have frequently been unsuccessful, boosting urban expansion into the rural areas, and generating at the same time urban brownfields (Tweeten, 1998). Often these lands are left vacant within the core city area and infill policies are not always successful (Harvey and Clark, 1965). As a result, cities tend to grow

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[1] Land take, sometimes as a synonym for soil consumption, is considered previously undeveloped soil consumed by built housing, utilities, transport, industry and commercial activities, and recreation, i.e. an appropriation of land to devote to infrastructures and related facilities (FAO and ITPS, 2015; Malucelli et al., 2014). Brownfields are abandoned or underused (industrial/commercial) facilities available for re-use that have real or perceived contamination problems and are mainly in developed urban areas not currently fully in use. Soil degradation derives mainly from the anthropogenic mismanagement of arable and grazing areas or, possibly, as a result of natural hazards. Land grabbing is instead considered large-scale land acquisitions whereby powerful foreign public or private investors create agreements with domestic states, which implies possession of and/or control.

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outward leaving patches of non-urban area within its centre (Bhatta, 2010). Nevertheless, the food system will function by the safe operating space of the planetary boundaries by 2050 (Conijn et al., 2018).

Urbanization is threatening surrounding croplands, in fact sprawl contributes to loss of farmlands (FAO and ITPS, 2015). In the United States only, the loss of 60,000 km^2 of both farmland and environmentally sensitive land, and 20,000 km^2 of other lands was predicted during the period 2000–2025 (Burchell et al., 2005).

The expansion of urban areas is a specific type of land use/land cover change but despite the existence of several global datasets on land cover (Bartholome and Belward, 2005; CIESIN, 2004; Elvidge et al., 2007; Goldewijk, 2005), only a few of them are accurate enough to allow a realistic estimate on a global scale. Among the global datasets focused on urban areas, there are Modis 500 (Schneider et al., 2009), Modis 1K (Schneider et al., 2003), Impsa (Elvidge et al., 2007) and Grump (CIESIN, 2004), compared by Potere et al. (2009) in terms of accuracy. Most of the studies focusing on monitoring the expansion of urban areas are at local (*e.g.* Malucelli et al., 2014; Pileri and Granata, 2014; Xiao et al., 2006), national (Gibson et al., 2015; Huang et al., 2016; Munafò et al., 2013; Salvati et al., 2013), or continental (Gardi et al., 2014) scale, and only few of them are at global scale (Schneider et al., 2009, 2010; Seto et al., 2011, 2012; van Vliet et al., 2017). However, the majority of these studies focus on accounting the extension of land subject to this type of change, and only rarely include the evaluation of the impacts on ecosystem services (Gardi et al., 2014; van Vliet et al., 2017).

Our main hypothesis is that when best soils become scarce, people compete to use those soils. From the beginning of settled civilisations, is that farmland was being taken over by urban growth[2]. The assumption is that settlements are most successful in good agricultural areas, but this has not been demonstrated formally. Best soils[3] guarantee successful agricultural communities that entice industries and services, and the zone grows (FAO and ITPS, 2015). We always think that level farmland with good soils provided the best sites for development, so that the very resource that engrossed settlement, was ultimately being consumed by it. If this were true, the oldest cities would have first, and immediately, consumed the best soils. Over a global scale and through the centuries, a trend between the intrinsic quality of the soils and its use for settlement purposes should be observable.

Are urbanization and food production in competition for the best soils? This question is the main objective of the present work, to determine if this is true or not.

2. Datasets and methods

We evaluated the relationships between human settlements, urban area expansion and soil productivity estimated from a soil classification (Buol et al., 2006; Schaetzl et al., 2012). The evaluation of country-based land taken at a global scale is presented for the period between 2000 and 2014.

2.1. Baseline datasets

A range of baseline spatial datasets have been used (Table 1): namely, a country layer, settlement list, soil type database and two built-up information layers for 2000 and 2014. A country information layer is necessary to derive statistics for each administrative area. In this work, the Global Administrative Area (GADM) database was used. The settlements list has been derived from the UN WUP database. This database has been used to assign the information on population for 2000, 2015, and the predicted growth for the period 1990–2030. The estimated year of the settlement establishment and geographic coordinates (an individual point) have been assigned to each settlement. Additionally, the location of each settlement has been verified via visual analysis using Bing Maps, and corrected if the point was falling outside the urbanised area of the settlement. The final settlement list consists of 395 cities and agglomerations over 155 countries.

The spatial information about soil type on land where built-up expansion occurs is provided by the Harmonized World Soil Database (HWSD) (Nachtergaele et al., 2008). Apart from soil types following FAO and World Reference Base (WRB) classification (IUSS Working Group WRB, 2015), this database offers information on several chemical-physical parameters. This dataset is available as a raster at 1 × 1 km. The database consists of rows and columns interrelated to harmonized soil property data: the standardised structure allows for the linkage of the attribute data with the raster map to query in terms of soil units and individual soil parameters. The land take between 2000 and 2014 has been estimated using a global multi-temporal dataset which reports on the presence of built-up areas. This information was extracted from the Global Human Settlement Layer (GHSL) (Pesaresi et al., 2016), which describes the spatial evolution of the human settlements in the past 40 years. The GHSL was produced from Landsat image records organized in four collections (years 1975, 1990, 2000, and 2014), and the data are available as multi-temporal built-up classifications at approximately 38 × 38 m spatial resolution. The consistency of the applied methodology for processing the image collections, the fine scale and global coverage of the product (just to number only some characteristics of GHSL), make these data an outstanding source of information for the analysis of urban expansion. The study presented in this work was performed using two datasets derived from the GHSL, *i.e.* built-up 2000 and built-up 2014 aggregated at 300 × 300 m spatial resolution. The entire analysis is conducted using the grid of these aggregate built-up layers.

In order to analyse the linkages between soil type and settlement dynamics, for each country the built-up values have been estimated for the areas where the HWSD data are available. The difference in spatial resolution of datasets cause an underestimation of the built-up totals in some areas, for example, costal zones.

2.1.1. Accuracy

The GHSL is one of a number of products at increasingly finer spatial resolutions that map built-up area globally from EO data. The GHSL was produced from Landsat image records organized in four collections (corresponding to the years 1975, 1990, 2000, and 2014), and the data are available as multi-temporal built-up classifications at approximately 38 × 38 m spatial resolution. The study presented in this paper was performed using two datasets derived from the GHSL, i.e. built-up 2000 and built-up 2014 aggregated at 300 × 300 m spatial resolution. In a recent paper of Blei et al. (2018) the accuracy of the Global Human

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[2] The mechanism, moving from natural uses or forestry through agriculture, causes an increase in labour productivity, implying that the surplus expands. Novel land uses are enough to bear a growing number of non-agricultural workers. They can be released from agriculture, and the goods can begin to be exported. These preconditions transform the economy leading to a shifting of prime agricultural land towards settlements (Chen, 2007; Dyson, 1996; FAO, 2008; Maxwell et al., 2000; Liu et al., 2014; Pauchard et al., 2006; Verburg et al., 1999). Rapid urbanization changes the land use affecting ecology, development, and food security (Cao et al., 2020; Chen et al., 2010; Guo et al., 2012; Liu et al., 2013; Rijal et al., 2020; Youssef et al., 2020).

[3] The Food and Agriculture Organization of the United Nations identified four pillars of food security as availability, access, utilization, and stability. Food security exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life. Best soils (Prime Farmland soils according to the U.S. Department of Agriculture) are those under conflict of land uses. Prime Farmland (PF) soils that have the best combination of physical and chemical characteristics for producing food, feed, forage, fiber, and oilseed crops. PFs have the soil quality, growing season, and moisture supply needed to produce economically sustained yields when managed according to acceptable farming methods. PFs have an adequate water supply, a favorable temperature and growing season, acceptable acidity or alkalinity, acceptable salt and sodium content, and few or no rocks. They are permeable to water and air. PFs are not excessively erodible or saturated with water for a long period of time, and they either do not flood frequently or are protected from flooding.

Table 1. Data sets used in the study [ref. Chandler, 1987; Modelski, 2003; Morris, 2010].

	Data set	Origin	Derived data	Resolution
1	Harmonized World Soil Database (2009)	FAO, IIASA, ISRIC-World Soil Information, Institute of Soil Science, Chinese Academy of Sciences (ISSCAS), and the Joint Research Centre of the European Commission (JRC)	Soil Productivity Index	1 km
2	Population, historical urban community sizes, and area of urban settlements	Dept. Economic and Social Affairs of the United Nations, U.S. Census Bureau, The World Bank, Chandler (1987), Modelski (2003), Morris (2010), Wikipedia	Settlement Lists	Urban area level
3	Cereal yields (2000, 2014)	FAO, The World Bank	Agricultural potential productivity	Country level
4	GHSL MT (1975–2014)	JRC European Commission	Built-up area 2000 (300m), Built-up area 2014 (300m)	300 m
5	GHSL MT (1975–2014) Settlement List	JRC European Commission and the derived data	Urban hot spots built-up area 2000, Urban hot spots built-up area 2014	300 m

Settlement Layer and of the Atlas of Urban Expansion were compared. The assessment was based on a sample of 200 cities. The overall accuracy of GHSL (local-based measures) was 84%, with 86% accuracy in the detection of built-up areas and 77% accuracy in detection of open spaces (14% and 23% of omission errors respectively for built-up and open space areas). The commission errors were 95 and 34% respectively or built-up and open space areas.

Table 2. Soil Productivity Index (SPI) attributed to individual type of soil according to WRB Great Groupings (IUSS Working Group WRB, 2015). The SPI scale, grouped by classes, defines highly productive soils (values > 10), average productive soils, and moderately productive soils (values < 6). All units are indices.

Reference WRB group		Soil Productivity Index
Acrisols	AC	4
Albeluvisols	AB	10
Alisols	AL	4
Andosols	AN	11
Anthrosols	AT	6
Arenosols	AR	6
Calcisols	CL	5
Cambisols	CM	9
Chernozems	CH	13
Cryosols	CR	6
Durisols	DU	5
Ferralsols	FR	3
Fluvisols	FL	6
Gleysols	GL	6
Gypsisols	GY	5
Histosols	HS	14
Kastanozems	KS	13
Leptosols	LP	6
Lixisols	LX	10
Luvisols	LV	10
Nitisols	NT	4
Phaeozems	PH	13
Planosols	PL	9
Plinthosols	PT	4
Podzols	PZ	7
Regosols	RG	6
Retisols	RT	10
Solonchaks	SC	5
Solonetz	SN	5
Stagnosols	ST	7
Technosols	TC	6
Umbrisols	UM	9
Vertisols	VR	12

2.2. Soil productivity

The intrinsic soil fertility (FAO and ITPS, 2015), here was estimated by applying the methodology proposed by Schaetzl et al. (2012) to WRB Great Soil Groups, following Buol et al. (2006). Table 2 presents the correspondence between WRB soil types and the proposed Soil Productivity Index (SPI). We have extracted from the Global Human Settlement Layer the WRB RGSs (column 2 in Table 2), and then we have attributed to individual soil WRB Great Groupings an individual Soil Productivity Index (column 3 in Table 2). In terms of the analysis of the conversion of fertile soils to urban land uses, we assume that land classified as 'fertile soil' could be eventually used for agricultural production. In this work we consider the potential use of soil for agriculture. We are aware that this is a great simplification, however our objective is to assess and discuss the loss of the soil, which potentially could be used for agriculture activity, and not actual arable land. Forest can be transformed to arable land, while transformation of an existing built-up area implies socio-economic impact: for the owner of the land, conversion from forest to agriculture, then to built-up area implies an increase in economic value. The main characteristic of this approach is that the SPI considers only the intrinsic soil fertility, while excluding any other factor (climatic, biophysical, social, political, economic, access and temporal variability) that may affect the actual land use or influence its agricultural productivity.

These SPI values are in a range between 3 and 14, where Histosols have the highest value, even if they are mainly distributed in areas where climatic and hydrological conditions may represent a limiting factor for the agricultural activity. There is an overall equivalence between the SPI used, and the indicators proposed by FAO and ITPS (2015, page 42), their correlations score a minimum r of 0.57. The HWSD was used to assign SPI values to each settlement from the settlement list (using ArcGIS application). In total, the SPI values have been assigned to a subset of the 395 settlements from the list; these 328 settlements are those with completed and verified data.

2.3. Regional analysis of land-take

We have simplified the scenario assuming that the land-take due to urban expansion occurred at the expense of arable land.

The selected agglomerations, urban hot spots, consist of ten urban agglomerations for Europe, Asia, Africa and America, and six for Oceania. For each settlement point, centroid of the urban area, a buffer of a 25 km radius was created. These surrounding areas were used to calculate the total sum of built-up as accounted by GHSL derived datasets.

3. Results

3.1. Urban expansion and soil productivity

Our results on the global distribution of the 395 cities and urban areas analysed say that, in total, cities and megacities have consumed around

14,400 km^2 of soils between 2000 and 2014 (Figure 1a). By comparison, one European conurbation, the Rhine-Ruhr region, including Düsseldorf, Cologne, Bonn, Dortmund, Essen, Duisburg, and Bochum, covers more than 7,000 km^2. Here, and in several areas worldwide, productive agricultural land is being developed, often characterized as consisting of low-density developments (Chin, 2002), and converted to suburban sprawl at increasing rates (Krannich, 2006).

The total global population of the urban areas analysed in this research was 945 million. Approximatively, half of the analysed population lives in urban areas built on soils with low fertility (SPI <6) and less than 10% on high fertile soils (SPI >11) (Figure 1a). One reason for this disproportion might be that the most productive soils are much less abundant globally.

Figure 1b shows the SPI and growth rate of the 50 fastest growing urban areas with at least 5 million inhabitants in 2000. The class of soil productivity is average or mediocre in all cases. In relation to the age of the establishment of the urban settlements did not show any significant correlation nor any clear trend, as depicted in Figure 2. This allows us to state that cities were not exclusively established on very fertile and productive soils (*i.e.*, Prime Farmland soils). In general, we observe that the quality of the soils on which modern cities are built was not a key factor in determining the dynamics of development, although there are few very populous cities that expand at the expense of highly productive soils.

3.2. Land-take and food security

The urbanization index, the ratio between urban areas and total area of a country, and the relative increase of urban areas is presented in Figure 3a and b, respectively. In Table 3, the top 60 countries with the highest value of land taken between 2000 and 2014 are reported. In absolute terms, the highest increase of urban areas is associated with fast growing economies such as China, India, Indonesia, South Africa, and Brazil, and also with developed countries, such as the USA, France, Germany, Italy, which between 2000 and 2014 experienced a severe economic crisis followed by a period of economic stagnation.

The baseline of urbanized areas was estimated at nearly 630,000 km^2 at the global scale for the year 2000, in agreement with Schneider et al. (2009). During the period 2000–2014, the global land-take caused by urban expansion was estimated at more than 145,000 km^2, which is equivalent to an increase of 23% with respect to the year 2000. This implies that under a business as usual scenario, in 2050 the built-up areas could be a level of more than 1,130,000 km^2. This prediction for the expansion of urban areas at the global scale is slightly lower than the range of values predicted by Seto et al. (2011), a growth of urban areas between 2000 and 2030 would range between 430,000 and 12,568,000 km^2, with an estimate of 1,527,000 km^2.

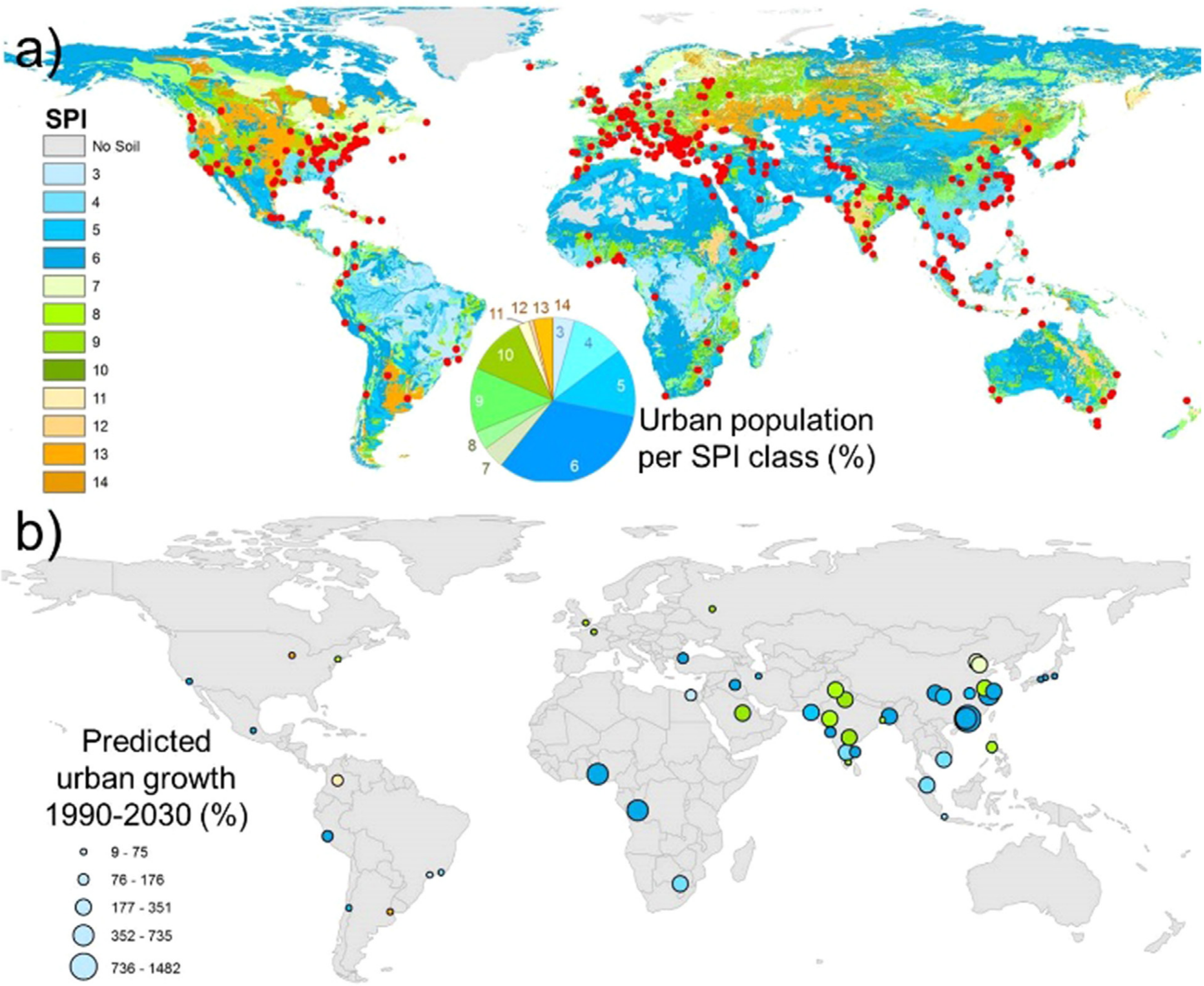

Figure 1. Soil Productivity Index classes (SPI) a) Red dots indicate human settlements considered in this study. The pie chart represents the percentage of urban population considered in this study (1 billion approximately) in relation to the class of productivity of the soil on which they live; b) Classes of soil productivity of the fastest growing urban settlements. The SPI scale grouped by classes: highly productive soils (values $>$ 10, brown scale), average productive soils (green scale), and moderately productive soils (values $<$ 6, blue scale).

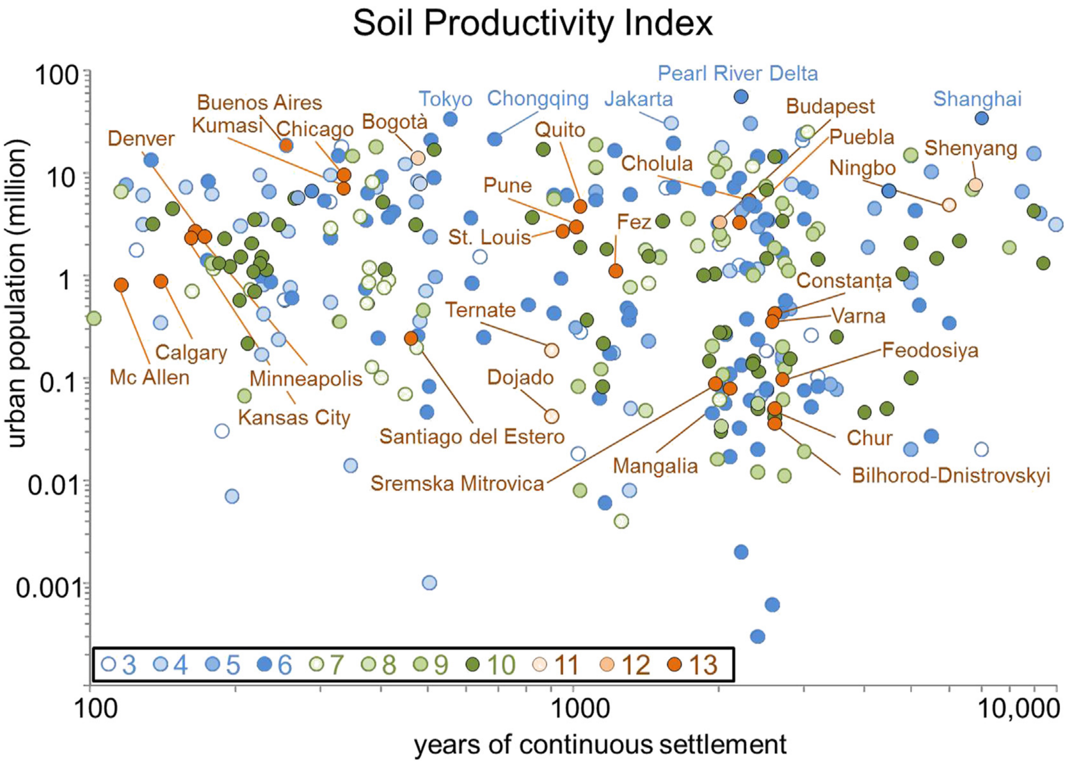

Figure 2. Soil Productivity Index (SPI) of major urban settlements plotted by period of continuous occupation of the land on the abscissa and current population in ordinate. The SPI chromatic scale is grouped by classes: highly productive soils (brown scale), average productive soils (green scale), and soils moderately (blue scale). Cities built on the worst soils are indicated in blue, while those built on the best soils in brown.

We are aware that intensification and increase in productivity would be possible (Bommarco et al., 2013), however this is not unlimited (Neumann et al., 2010). Agricultural productivity in most western countries is stable, or slowly increasing, while improvement that is more important can be expected in the developing countries. However, this intensification will imply further impacts on the environment, and will rely on the availability of resources that are already limited or increasingly expensive (phosphorus, energy, etc.). Removing 145,000 square km of land from production is not fatal, but is a part of an essentially irreversible process, and will determine the progressive reduction of a non-renewable resource. The possibility of bringing brownfields back to production is quite unlikely as in most cases, the de-sealing of brownfields or former urban areas will create parks, green areas within, or surrounding the cities, and not agricultural production fields. Furthermore, we are all aware that already several countries in the world are not self-sufficient. This does not imply an issue of "food security" according to the standard definition. However, if we consider that the human population, in order to be "food secure", would access a global stock of food, any erosion/decrease of global food production will affect global food security, maybe in the medium or long term.

3.3. *Land-take in selected urban hot spots*

Five out of the ten fastest expanding urban hot spots are in Africa, reflecting the demographic dynamics of this continent, but are also driven by urban migration from rural areas (Figure 4). There are only three of these fast expanding urban areas that are among the ten most populated: Shanghai, New York-Newark and Cairo, and this could be explained by the limited area analysed (core of urban areas).

If we consider the three US urban hot spots analysed, New York, Chicago, Los Angeles metropolitan areas, the actual population density decreases in the following order: Los Angeles, New York, Chicago. While the growth of urbanized areas within the core of the cities is higher for New York (88 km^2), followed by Los Angeles (20 km^2) and Chicago (9 km^2), the overall urban population increase was comparable in New York and Los Angeles (+5.0% and +4.9%), but decreased in Chicago (-6.2%). These tendencies are partially reflected in urban growth.

4. Discussion

According to the population dynamics over the past twenty years, the cities where the population increased by more than 100% are mainly in Asia (twenty-six megalopolis), followed by Africa (Johannesburg/East Rand, Kinshasa, Lagos, Luanda), the Middle East (Riyadh and Istanbul) and the Americas (Atlanta and Bogotá). In China, a country known for its fast rates of urbanization, the highest rates of urbanization (current and in perspective) occur along the Pearl River Delta, where during the eighties, an interweaving net of rivers flowed through Cambisols, Fluvisols and Anthrosols (IUSS WG WRB, 2015) soils, which were used mainly as rice paddies, annual field crop or orchards (Chor-pang and Clifton, 1985). At that time, the region was mostly rural, with a population of roughly 10 million people scattered between several medium-sized cities, including Dongguan, Foshan, Guangzhou and Shenzhen. These cities have merged into an interconnected megalopolis that, if seen as one urban body, had expanded from 4.5 to 7.0 thousand square kilometres (data from the World Bank and AsiaPop project) with a current population of 42 million (Gaughan et al., 2013). Apart from the Pearl River Delta, Chinese megalopolises grow on moderately productive soils such as Arenosols (Hangzhou), Solonchaks (Chongqing), Stagnosols (Beijing), or Solonetz (Xi'an), indicating that even these periurban soils of moderate quality can achieve high yields when appropriate management techniques are employed. Shanghai consumed thousands of square kilometres of Fluvisols, soils with an intermediate productivity potential. In the rest of the world, scarcely productive Ferralsols lay below Cairo (Al-Qahirah) and Belo Horizonte, while very modest Acrisols sustain the expansion of megalopolis like Atlanta, Ho Chi Minh City (formerly Sài Gòn), Kuala Lumpur and Lagos.

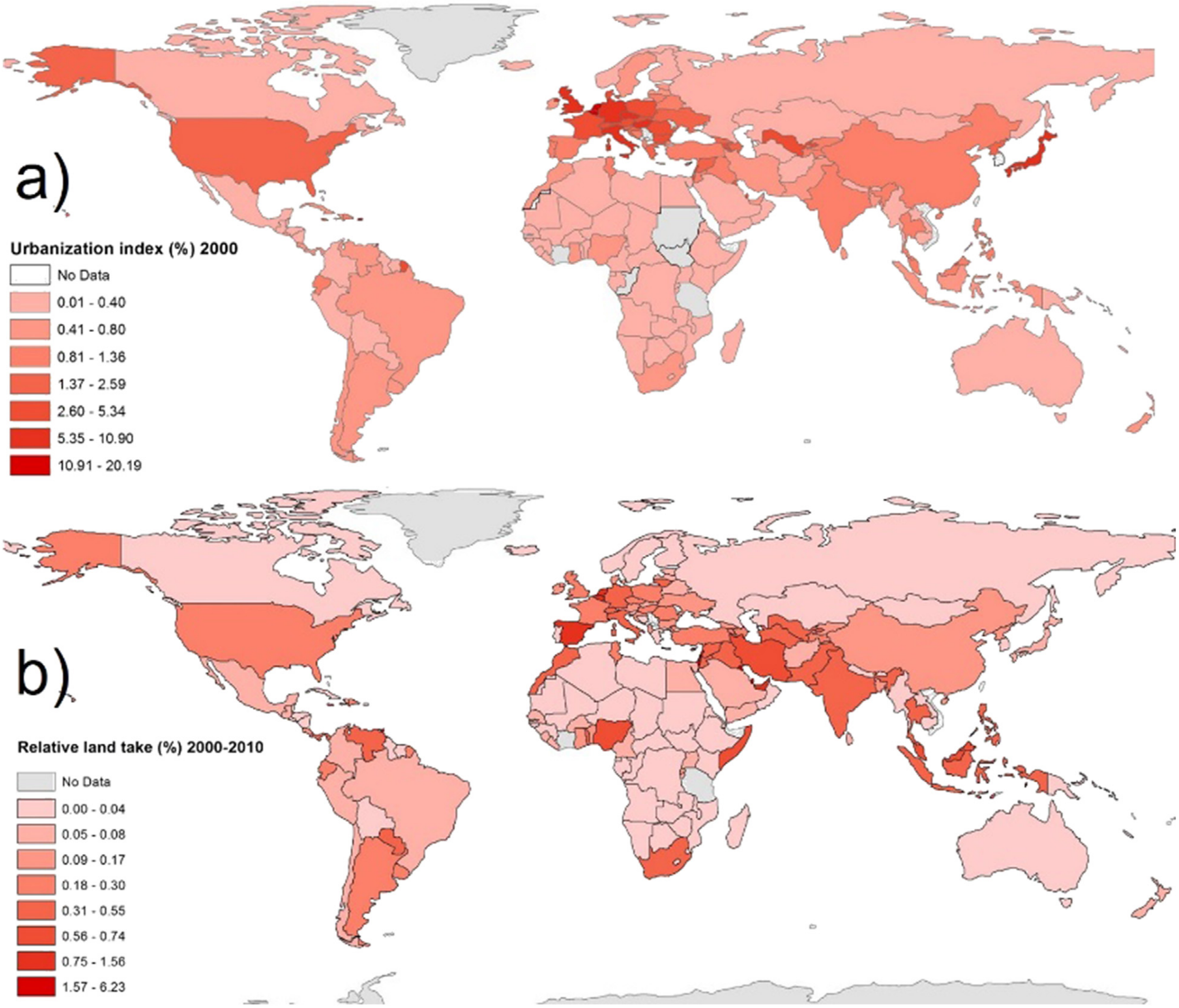

Figure 3. Land take estimated using a multi-temporal dataset reporting on the presence of built-up areas, extracted from Landsat derived GHSL dataset aggregated at 300 × 300 m spatial resolution. The built-up values per individual country have been estimated for the areas where the HWSD data are available. a) Urbanization index: ratio between artificial area and total area at countries level (relative urban cover, year 2000); b) Relative land take (period 2000–2014) where variation is expressed as percentage of the artificial area in 2000.

Several studies at regional or local scales show rates of urban growth that are considerably higher, but they generally refer to specific cases or urban agglomeration, where the urban growth rate can be considerably higher than the average values at the national scale (Xiao et al., 2006). While the global land-take between 2000 and 2014 represents only 0.1% of the global continental area, and because the current estimates on the percentage of soils having favourable conditions for agriculture (a more ample concept than SPI which focuses on soil intrinsic fertility) predict a value ranging between 13% and 18% (Jones et al., 2012). It can be estimated that land-take affects roughly 1% of the naturally fertile soils, suitable for agriculture production. The concept of "favourable conditions", refers to soils without major constraints related to climate (too wet or too dry, too hot or too cold), to topography (too steep, too shallow), or to other limiting factors (too salty, contaminated, etc).

4.1. Land-take methodological issues

Several non-demographic elements, including land use issues, will shape the dimension of global urban extent in future decades (Seto et al., 2011). Thus, using multistage images, remote sensing techniques can help characterize trends of urbanization and soil-related processes (Bouhennache and Bouden, 2014; Haas et al., 2015; Mundia and Aniya, 2005; Potere et al., 2009; Schneider et al., 2009; Thebpanya and Bhuyan, 2015; Villa et al. 2014, 2018; Xiao et al., 2006; Yan et al., 2009). Recent approaches are based on night-time light images (Pestalozzi et al., 2013) and on Google™ Earth Engine (Padarian et al., 2015). In particular, landscape metrics are used to explore fluctuations in landscape configuration and to highlight potential environmental impacts. This can be coupled with public soil surveys, which have demonstrated the value of data collected by the public on such subjects (Bone et al., 2012), raising awareness on the importance of soils, and strengthening the citizen's connectivity to the soil resource (Rossiter et al., 2015).

4.2. Land-take, agriculture, and food security

Despite several studies showing the existence of unexploited margins for increasing crop yields in many areas of the world (Lobell et al., 2009), and the promising approach of sustainable agricultural intensification (Rudel, 2020), as a result of urban expansion, land-take is one of the most irreversible forms of soil degradation (Gardi et al. 2014, 2016; Salata and Gardi, 2014). And, soil conservation is key for solving the global environmental sustainability challenges of food security (McBratney et al., 2014).

According to our estimates, during the period 2000–2014, urban expansion caused more than 14.5 million of land-taken hectares, concentrated mainly in countries with fast growing economies, China, India, Indonesia, South Africa, and Brazil, or with high demographic pressure (Nigeria, Democratic Republic of Congo), with an overall impact on agricultural production capability estimated in 63 million tonnes of cereals.

More than one third of the land-take occurred in Asia. As ecologically, and economically sound opportunities for increasing cultivated area are limited in many countries and virtually non-existent in several Asian countries, farmers will meet huge increases in food request mainly through intensification in productivity (Chartres and Noble, 2015). So, with top priority given to agriculture, China succeeded in feeding its population in the past decades, but today to feed its future peak population China needs to secure a minimum cultivated land area of 107 million ha (Chen, 2007). In the 1990s, the transformation of the agriculture sector in China led to an increase in agricultural productivity (Yan et al., 2009): the increase in the agricultural production brought by land transformation resulted mainly from the transformation of poor quality soils into cropland (Tan et al., 2005). In fact, the productivity of arable land occupied by urban expansion was much higher than that of the newly cultivated lands in the regions where the quality of newly cultivated lands was poor (Yan et al., 2009). Nevertheless the occurrence of ecological compensation mechanisms (Yang et al., 2020), the current Chinese policies intended to safeguard agricultural soils by moving people towards urban areas speed up the land-take process (Deng et al., 2015). According to our data, in the 2000–2014 period, China lost more than 3 million ha of land, the vast majority of it was agricultural land.

In India, in the fertile strip of Upper Ganga-Yamuna doab in Uttar Pradesh, Fazal (2000) reported a loss of more than a thousand hectares of agricultural soils between 1988 and 1998 in the city of Saharanpur due to urban expansion. Of these, 527 ha were in Class I, 940 ha in Class II and 216 ha in Class III on the basis of land capability classification, LCC[4]. The total estimated loss of grain production in the study area was about 5049 tonnes (Fazal, 2000). Our estimates for India indicate more than 1 million ha land-taken.

Land use conversion is, however, characterized by an increase in urban areas and in intensive agriculture, forest transition and new frontier clearings (Chen et al., 2014; Tsiafouli et al., 2015), but not when there is economic collapse, see the 1990s in some parts of Europe (Kamp et al., 2015). Analyses of the land productivity and land use show that the EU is experiencing a consistent decrease in production capacity (Tóth, 2012; Gardi et al., 2014; Malucelli et al., 2014). Globally, using individual country population and GDP projections (Tilman et al., 2009), and adjusted per-capita biocapacity (considering population increase), Weinzettel et al. (2013) estimated a 70% increase in the global land footprint between 2004 and 2050. Where, the increased pressures on the existing soils can lead to worsening soil degradation processes (Rickson et al., 2015). If we learn lessons from the past, an augmented food demand and increasing pressure was put upon the soil to provide more resources for a developing Roman economy. Our ancestors with systematic clearing and ploughing soon exhausted their agricultural soil, which eventually became infertile. Most of the nourishment of the

Table 3. Land take for the 50 countries with the highest estimated urban expansion during the period 2000–2104. Land take expressed in thousands of square kilometres.

Country	Land take 2000–2014 ('000 km^2)
China	30.2
United States of America	20.4
India	10.4
Indonesia	5.5
Nigeria	4.9
South Africa	4.4
France	3.2
Germany	2.9
Brazil	2.5
Italy	2.3
Russian Federation	2.3
Mexico	2.2
Democratic Rep. of the Congo	2.1
Japan	1.8
Argentina	1.6
Spain	1.6
Ukraine	1.6
Ghana	1.6
Thailand	1.5
Turkey	1.4
Canada	1.4
United Kingdom	1.3
Netherlands	1.3
Australia	1.3
Poland	1.2
Pakistan	1.1
Vietnam	1.1
Malaysia	1.0
Iran (Islamic Republic of)	1.0
Cote d'Ivoire	1.0
Ethiopia	1.0
Romania	0.9
Egypt	0.9
Malawi	0.8
Portugal	0.8
Myanmar	0.8
Iraq	0.7
Somalia	0.7
Belgium	0.7
Algeria	0.6
Zambia	0.6
Philippines	0.6
Morocco	0.5
Korea	0.5
Bangladesh	0.5
Angola	0.5
Yemen	0.5
Tanzania	0.5
Saudi Arabia	0.5
Sudan	0.5
Guinea	0.5
Argentina	0.5
Colombia	0.5
Sierra Leone	0.5
Hungary	0.4
Mozambique	0.4

(continued on next page)

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[4] According to FAO, LCC principles are: (i) areas of land are put into classes ranging from best (Class I) to worst (Class VIII), (ii) land allocated to a particular capability class has the potential for the use specified for that class and for all classes below it, (iii) the perspective is one of a land use hierarchy: some land uses are more desirable than others (cultivation is preferable to pastures, pastures preferable to woodland etc.), (iv) allocation into a particular capability class is based on limitations of the land or restrictions on the range of uses or the management/conservation practices needed for the particular use, (v) commonly considered limitations are erosion hazard, excess water, depth, stoniness, climatic limitations, (vi) there is a strong bias towards conservation needs (for protection against erosion).

Table 3 (*continued*)

Country	Land take 2000–2014 ('000 km^2)
Czeck Republic	0.4
Burkina Faso	0.4
Austria	0.4
Uzbekistan	0.4
Zimbabwe	0.4

ancient Roman population was actually imported from present-day northern Tunisia, Algeria, and western Libya owing to its greater agricultural productivity as related to the depleted Roman soils of those times. Despite this, the Maghreb has now lost much of its soil productivity, and today there is strong agricultural pressure on marginal lands due to human population increases, and global food security will remain a worldwide concern for at least the next 50 years (Rosegrant and Cline, 2003).

In Europe in the last decades we observe a negative correlation between annual economic growth and the rate of cropland conversion (Tóth, 2012). In Asia, Europe and North America additional agricultural production will be driven almost exclusively by yield improvements (OECD/FAO, 2015). Yield improvements and additional agricultural area are expected in South America, and more modestly in Africa, although further investments in both yield improvements and/or additional agricultural area (*e.g.* Coomes et al., 2015; Exner et al., 2015; Phalan et al., 2014; Pradhan et al., 2015) could raise yields and production significantly (OECD/FAO, 2015).

Rather optimistically, Smit et al. (2001) sustain that up to one third of the world's food supply could be grown in backyards, urban allotments, or community gardens, or using soil-less systems (Mageau et al., 2015). However, a study in a UK urban landscape estimated a yearly production sufficient to supply the population for about 33 days (Grafius et al., 2020). In fact, at least two thirds of the global food supply originates from rural areas. Rural areas are constantly losing land, leaving room for houses and infrastructures. In fact, the total urban area quadrupled worldwide over the last thirty years while urban population at national levels doubled (Seto et al., 2011). Apart from the physical loss of land, the reasons for these cropland losses are generally due to underperformance in the economic self-sustainability of farms rather than urban invasion (Tweeten, 1998). Urban land expansion following a universal pattern across different countries (Pestalozzi et al., 2013) is growing faster in low elevation coastal zones than in other areas (Munafò et al., 2013). Changes of soil sealing and soil landscape patterns depend normally on the neighbouring landscape patterns (Xiao et al., 2013). Particularly in developing countries, urban growth is considered to be taking place on agricultural lands of highly productive value (Seto et al. 2000, 2012; Wu et al., 2015; D' Amour et al., 2017). Furthermore, these land use changes could be worsened by bioenergy development, as the potential competition between energy crops and food crops can result in increased food commodity prices (Littlejohn et al., 2015).

Several studies have emphasized the impacts of land use change on the potential to maintain food self-sufficiency in China (Rozelle and Rosegrant, 1997; Feng et al., 2005; Yan et al., 2009). Peri-urbanization, which has been documented in China, Indonesia, and other Asian countries (Huang et al., 2015; Kontgis et al., 2014; Zhang et al., 2019), occurs where new urban expansion takes place in locations tens of kilometres from the core, with nearly half of population expansion occurring in peri-urban communes. Peri-urban areas are particularly vulnerable to land acquisitions and tenure variations with disrupting socioeconomic effects and ecosystem degradation (Seto et al., 2012). Instead, in Mediterranean countries the expansion of small-medium urban agglomerations has led to an increase in fragmentation (Marraccini et al., 2015). So, should we thus try to preserve nature outside towns by densifying our towns, or should we intensify agriculture, again leading to more land where nature can be protected (Foley et al., 2005; Shackelford et al., 2015)?

4.3. Indirect land use change

The global demand for food and feed crops remains, and may lead to someone producing more food and feed somewhere else, which can imply land use change by changing, for example, forest into agricultural land. In the case of the European Bioenergy policy (Hiederer et al., 2010), the concept of Indirect Land Use change (ILUc) was introduced, which considered the change in land use determined by the production of biofuels on existing agricultural land (*e.g.* Palmer, 2014). A similar

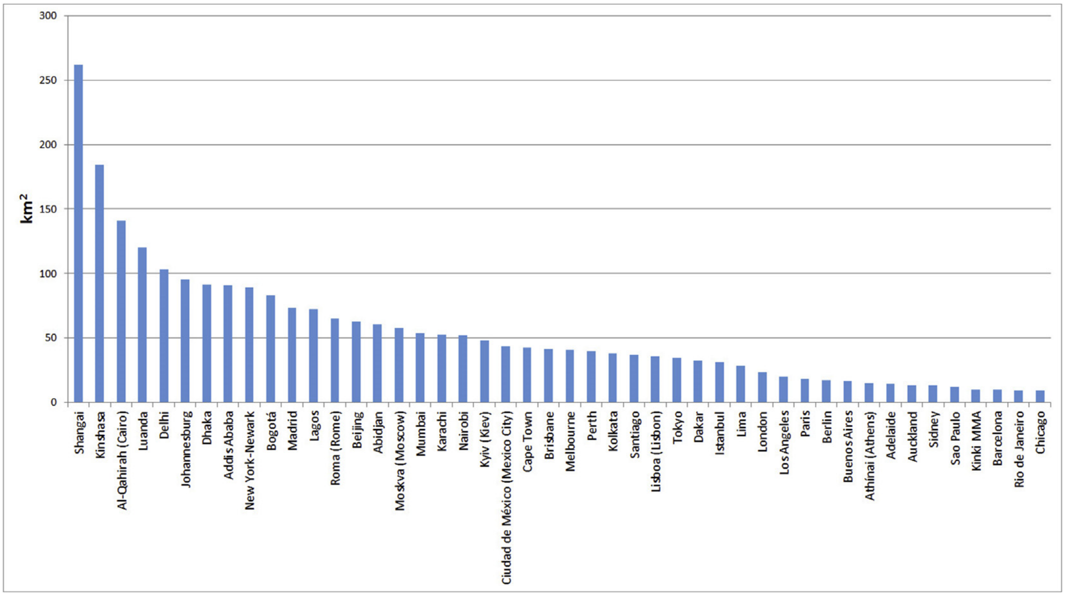

Figure 4. Urban expansion (2000–2014) within 25 km radius from city centroids, calculated for 46 urban hot-spots, ten urban benchmark agglomerations per Europe, Asia, Africa, America, and six for Oceania. Land use transformation within the core of the urban areas expressed via population growth. The surrounding areas were used to calculate the total sum of built-up as accounted by GHSL derived datasets.

approach could be adopted for the evaluation of the ILUc consequent to urban expansion and land take. For instance, if in the Netherlands or Belgium 10,000 ha of agricultural land were converted into urban areas, these countries can compensate the losses of agricultural production by importing agricultural commodities. However, if 10,000 ha of land in the Netherlands can produce up to 100,000 tonnes of cereals, in other parts of the world, especially in developing countries, to produce the same quantity of cereals could require an area at least four times larger (FAO, 2014). The land use displaced through trade, *i.e.* the land use required for imports, varied proportionally with income and is inversely related to country size, with small and high-income countries importing relatively more (Weinzettel et al., 2013). So, the trade of farmland in less developed countries is an issue of large-scale land acquisitions known as land grabbing (World Bank, 2014). This, grabbed land is related to land-take and food security, or better, to the fear of food insecurity (Borras and Franco, 2012; Holmén, 2015; Rulli and D'Odorico, 2014; Liao et al., 2016). It is based on the ascertainment that land, and especially good quality agricultural land, is a limited resource. Land grabbing is a global phenomenon (FAO, 2009, 2012) which involves at least 62 grabbed countries and 41 grabbers, and affects all continents except Antarctica. The results of our study, interpreted in this light, tell us that the food security of a developed country is not jeopardized by urbanization, essentially in all cases, but reasoning in terms of indirect use or of grabbed land elsewhere, on a global level there could be an impact.

4.4. Land-take within the major urban hot spots

Most of the fast-growing urban hot spots are in Africa, where the growth is generally driven by population dynamics. In all the African cities, but not in Cairo, the urban population has approximately doubled from 2000 to 2014, while in most of the large Asian cities the population increase was lower. Here, urban growth of super large cities consumed smaller quantity of farmland when accommodating a certain amount of urban population (Hu et al., 2020).

The data we produced show additional characteristics of the land-take process, for example, in New York there is a prevailing densification process, while in Los Angeles and Chicago urban sprawl is dominant. Chicago, in particular, was still spreading, despite the population decrease.

However, not only are the best quality soils being threatened by urban growth, but a large percentage of our food supply is grown on soils that are not our best quality soils. The simplification deriving from the interpretation of the results of our study must not therefore forget that while many urban areas consume moderate quality soils this does not directly mean that they are not threatening food security and other services provided by soils. In addition, the performed analysis is not exhaustive, as it does not include the whole urban area extension, especially for the most populated and/or most dispersed cities. Also, the extent of some of the hot spots exceeds the analysed area (nearly 2000 km^2). Therefore, this analysis is a tentative study of the cross regional trends, which should be performed in more detail to reach absolute conclusions on the overall growth of these urban hot spots.

4.5. Limitations

Discussing the limitations of our approach and potential biases due to the assumptions made, it is important to say that food security is a complex concept and has multiple dimensions, according to its most prominent definition availability, accessibility, and utilization. Our aim is not to provide general inferences regarding global food security, but to study the availability dimension, namely local production. Although, agricultural production used to be strongly dependent on local environments sustaining smallholder households in many world regions (Vanek et al., 2016), paradoxically, countries can urbanize all of their croplands/productive soils and still be food secure, if they import their food and have the financial means to access it. The focus of our analysis is the soil factor only, from the point of view of its intrinsic quality.

5. Conclusions

Urbanization and food production are not in competition for the best soils.

Given the complexities of urban systems, we have simplified the issue with the assumption about the food production value of the land converted by urban development and the quality of its soils. Given that soil type is a very crude measure of food security, there are no global-scale studies that cover the relationship (if any) between soil quality, urban expansion and food security. From an historical perspective, between soil quality, urban settlement and urban expansion, although several entanglements, there does not exist a distinctive relationship: ancient and recent cities do not show a distinct and characteristic pattern of land take.

The change in the extent of built-up area is not proportional to population growth on a country basis; however, there is a common increment from built-up areas in all countries, independent of population dynamics.

The main soil qualities that are considered by IIASA and FAO as soil health indicators are organic matter, nutrient availability, workability, oxygen availability to roots, nutrient retention capacity, toxicity, salinity and rooting conditions. These are mapped at global scale in the Harmonized World Soil Database v1.2. Their distribution in health classes substantially overlaps with the mapping of soils in classes of intrinsic productivity. The core message is that the best soils are a scarce resource with increasing limitations to their use for the production of food. This is the main reason why highly populated settlements, regardless of time and location, consumed less highly productive soils. Most likely, this will happen also in perspective. Hot spots affecting high quality soils do not represent a global trend. The best quality soils for food production are not specifically threatened by more voracious megacities; different is the case of land-take when sparse and widespread urbanization occur, although it is not the purpose of this work. However, the consequences of urban growth on the potential agricultural production capability confirm that intensively managed ecosystems decrease the potential of soils to deliver more ecosystem services (*e.g.* Gardi et al., 2016).

On the base of the selected proxies, we estimated that for the period 2000–2014 more than 145,000 km^2 of land were converted in urban/artificial land uses, withdrawing most of them from the agricultural production. Assuming that all these lands would be allocated to cereal production, and assuming a conservative estimate of cereal yields in these areas, we estimate a potential productivity loss to about 60 million tonnes of cereals, representing approximately 2.5% of the global cereal production.

The impact of urban expansion on soil resources causes soil degradation, and these figures underline the role of urban growth and the associated land take processes which should be more carefully evaluated in the context of global change. Soil sealing and land-take are not the most important degradation processes in terms of area affected, but are so, due to their irreversibility and impact on agricultural production. Interesting insights can be provided by the analysis of the relationships between dimension of the settlements, urban land use efficiency and soil productivity.

This issue, and more in general the soil and land degradation processes, are increasingly included in the political agenda: from the international scale, the 17 interlinked Sustainable Development Goals (A/RES/71/313 E/CN.3/2018/2) and zero net land degradation by UNDP, to the regional and national one. In most of the cases, however, we are still at the stage of "declarations of intention" and very few concrete initiatives for limiting land take have been implemented.

Declarations

Author contribution statement

Gardi Ciro: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed materials, analysis tools or data; Wrote the paper.

Florczyk Aneta Jadwiga: Performed the experiments; Contributed materials, analysis tools or data; Wrote the paper.

Scalenghe Riccardo: Performed the experiments; Analyzed and interpreted the data; Contributed materials, analysis tools or data; Wrote the paper.

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Declaration of interests statement

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Additional information

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