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TOPICAL REVIEW

How to map soil sealing, land take and impervious surfaces? A systematic review

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Keywords: soil sealing, soil, impervious surface, land consumption, soil consumption, land take, sustainable urban planning

Supplementary material for this article is available online

Abstract

Soil degradation is one of the main environmental issues within the international agendas on sustainability and climate adaptation. Among degradation processes, soil sealing represents the major threat, as ecosystem services dramatically decrease or are even nullified. The increasing use of big open data from satellites combined with AI algorithms are making geodata mining and mapping techniques essential to quantify soil sealing. Different keywords are adopted to define the phenomenon. However, at present, review articles presenting the state-of-the-art on mapping soil sealing by including the most common definitions are currently not available. Hence, we analyzed: (a) impervious surface, (b) soil sealing, (c) land take, (d) soil consumption, (e) land consumption. We provide a systematic review of remote sensing platforms and methodologies to map and to classify soil sealing, by highlighting: (a) definitions; (b) relationships among study areas, scales, platforms, resolutions, and classification methodologies; (c) emerging trends and policy implications. We performed a systematic search on Scopus (from 2000 to 2020), identifying 1277 papers; 392 focused on mapping soil sealing. 'Impervious surface' is the dominant definition. The phenomenon is more studied by the USA, China and Italy and, 'soil sealing' is recently more adopted in EU. Most studies focuses on mapping soil sealing at urban scale. We found Landsat are the most adopted platforms; they are frequently used for multi-temporal analyses. Eleven methodologies were identified: automatic classifications are the most adopted, dominated by pixel/sub-pixel-based approaches; other methods include Band Ratios, Supervised, OBIA, ANN. The majority of mapping analyses are performed on 30 m resolution in areas of 1000–10 000 km^2. Landsat images are less used for smaller areas. In conclusion, as study area size increases, a decrease in image resolution with the use of more completely automatic classification methodologies is recorded. However, most studies focuses on comparing classification techniques rather than supporting policy making for sustainable urban planning. Thus, we encourage to fill the gap by developing approaches that applicable to international policies.

1. Introduction

1.1. Soil sealing: defining the phenomenon

Soil degradation is recognized as one of the main environmental issues debated in the international and national agendas on sustainability and climate adaptation (Montgomery 2012, Koch *et al* 2013, FAO 2015, European Environment Agency 2016). Among degradation processes, land-surface impermeabilization represents the major threat for soils, as ecosystem functions and services drastically decrease or are even nullified (Scalenghe and Marsan 2009). In fact, despite different definitions reported in the scientific literature, such irreversible human-driven land-use dynamics are related to the covering of natural and semi-natural soil with impermeable surfaces such as concrete, asphalt and other impervious materials (Prokop *et al* 2011).

Recently, due to international strategies and policies adopted for increasing sustainability and resilience of urban ecosystems such as 'Zero Land Take 2050' (European Commission 2011, Prokop *et al* 2011, Decoville and Schneider 2016), the global attention on 'soil sealing' notably increased, by involving both scientists and stakeholders from different disciplines and institutions: civil and environmental engineers, urban planners, ecologists, geographers, geologists, economists on one hand; policy makers from different level of institutions and governance on the other one. Such increasing attention is related to the multiple and multiscale effects of land cover/land use changes of soil sealing which affects forests, grasslands, agricultural lands, and bare soils (Burghardt 2006, Murata and Kawai 2018). Moreover, as reported in the latest AR6 IPCC Report on Climate Change, the frequency increase of extreme meteorological events such as heat waves, extreme rainfall, and floods will exacerbate impacts of soil sealing on urban ecosystems (2021).

Direct impacts of soil sealing are strictly related to drastic changes in hydrologic cycle such as alteration of urban runoff and infiltration processes, reduction of groundwater recharge, which might increase the hydrogeological risk and decrease of water quality (Arnold and Gibbons 1996, Shuster *et al* 2005, Pistocchi *et al* 2015). Important impacts of soil sealing also directly affects ecosystems and, therefore, goods and services they provide: landscape fragmentation and ecosystem degradation, changes in thermoregulation, carbon sequestration and pollution mitigation as services and functions provided from vegetation systems (Scalenghe and Marsan 2009, Dos Santos *et al* 2017, Fini *et al* 2017). Moreover, soil sealing is recognized as one of the first causes of biodiversity loss worldwide (Seto *et al* 2012). In urban context it affects human well-being and health by reducing green and open spaces (Artmann *et al* 2019). Finally, by the expansion and sprawling of urban areas, it affects agricultural and semi-natural lands which are covered by new buildings and terrestrial infrastructures, reducing the availability of food and jeopardizing food security, especially in developing countries (Gardi 2017).

Due to its inherent geographic dimension, studies about soil sealing are often spatially-explicit and quantitative, generally oriented to map the phenomenon or to detect temporal changes. Hence, a common requirement is to quantify, to map and to geovisualize the amount of sealed surfaces. In addition, many scientists investigate the spatial evolution of soil sealing over the years, by performing multitemporal analyses to identify land cover changes related to the urban expansion. Finally, an important task is to annually monitor the phenomenon and to verify the effectiveness of new laws and regulations promulgated to limit soil sealing (Langella *et al* 2020).

Despite in the last 20 years, scientific literature includes a significant number of research articles which deal with this issue, only three review articles focused on methodologies to map the phenomenon (Slonecker *et al* 2001, Weng 2012, Wang and Li 2019). However, such review articles only include 'impervious surface' as a search keyword, excluding other common terms and definitions of the same phenomenon. By considering the growing need to respond both at Sustainable UN Development Goals as well as international, national and regional policies for limiting such phenomenon, we firstly performed a comprehensive screening of definitions and terms commonly adopted in scientific literature:

(a) soil sealing: 'the destruction or covering of soils by buildings, constructions and layers of completely or partly impermeable artificial material (asphalt, concrete, etc)' (Prokop *et al* 2011);
(b) land consumption: 'the change from a non-artificial to an artificial land cover of the ground, with the distinction between permanent land consumption (due to permanent artificial cover) and no-permanent land consumption (due to a reversible artificial cover)' (Strollo *et al* 2020);
(c) soil consumption: it is used as a synonymous of 'land consumption' and it describes the transition from natural to artificial land (Amato *et al* 2017). It is scarcely used in the scientific literature, however Scalenghe and Marsan (2009), one of the most important articles that highlights the impacts of soil sealing, adopts this term;
(d) impervious surface: 'can be generally defined as any material-of natural or anthropogenic source-that prevents the infiltration of water into soil and thereby changing the flow dynamics, sedimentation load and pollution profile of storm water runoff' (Slonecker *et al* 2001); in addition 'features that commonly account for 80% of impervious cover include buildings e.g. roofs, driveways, and patios, roads, and parking lots' (Theobald *et al* 2009);
(e) land take: according to Prokop *et al* (2011) the term refers to the rising of artificial areas over time. This practice is usually performed to the detriment of agricultural areas.

According to a recent study on 'Standard and Strategies for the reduction of land consumption' (2020), which investigated definitions within scientific literature and EU land policy context, 'soil sealing', 'land take', 'soil consumption', and 'land consumption' are, at present, the most adopted terms. The authors suggested to prioritize the term 'land take' (Marquard *et al* 2020). It is worth noting that, since 2002, the European Commission used the term 'soil sealing' referring to the phenomenon of imperviousness of soil (Commission of the European Communities 2002). Since then, 'soil sealing' as keyword started to be used by other European national institutions and in the scientific literature. Furthermore, in the UN Sustainable Goal (SDG-11), the SDG-indicator 'Ratio of land consumption rate to population growth rate', defined this land-surface impermeabilization phenomenon as 'land consumption'.

In this perspective, review articles presenting the state-of-the-art on mapping soil sealing and analyzing the most common definitions are currently not available. Hence, this study attempts to fill the gap by including in the systematic review five keywords: (a) impervious surface, (b) soil sealing, (c) land take, (d) soil consumption, (e) land consumption. In the present study, authors adopt the term 'soil sealing' to define such phenomenon.

1.2. Remote sensing technologies to map soil sealing

In last decades, the increasing availability of data from aerial platforms made remote sensing together with Geographic Information Systems (GIS) the most widely adopted technology to map and to assess soil sealing, at different geographic scales of analysis. In fact, satellites, airplanes, and fixed-wing UAV platforms, equipped with a wide range of sensors, can provide an ever more increasing spatial, temporal and radiometric resolution. At present, the spread of big open data from satellites combined with the development of AI algorithms are making geodata mining and mapping techniques essential to quantify soil sealing at different spatial and temporal resolutions. Indeed, the use of GIS and geodata allows to analyze and to model spatial data at different scale, from small portion of land surface, up to the national or global scale (Slonecker *et al* 2001, Zhang *et al* 2019). Other technologies such as field survey, census data or ground-based data collection are generally costly and time-consuming. However, they were frequently used in recent past years for monitoring soil sealing (Lu and Weng 2006). An important example is represented by LUCAS Program (Land Use/Land Cover Area Frame Survey) which was managed by EU Member States to measure the nature of land cover and its use (Ballin *et al* 2018).

Overall, remote sensing technologies present many advantages: (a) they enable to perform spatial analyses on large areas (Weng 2020); (b) they can provide open access big spatial data (i.e. NASA Landsat or EU Copernicus satellite missions); (c) they can allow high-frequency re-visit time over the same area, making feasible multitemporal analyses and monitoring soil sealing processes over years and decades. Indeed, two important studies which express the strength of combining open satellite data with GIS modelling are represented by the use of imageries from the Landsat satellites constellations and the Sentinel missions; the former adopted Landsat image series to map the urban expansion in 50 global cities (Bagan and Yamagata 2014); the latter provided the 'Urban Atlas' from the EU monitoring service which used Copernicus Sentinel Satellite to map soil sealing in EU27 plus European 11 countries (European Commission 2020). In fact, through the launch of Sentinel missions in 2015 different satellites are recently available by providing open spatial data to monitor worldwide land use/land cover changes and to detect new urbanization. It is noteworthy the case of the Italian National Institute for Environmental Protection and Research (ISPRA) that since 2015 adopted Sentinel satellite open data from Copernicus Program to monitor soil sealing for the whole Italian country, annually (2021).

1.3. Methodologies and approaches to mapping soil sealing

A variety of classification methodologies and approaches have been used to map soil sealing—from the long-stand photo-interpretation of orthophotos to advanced subpixel-based modelling and extraction from satellite imagery. Based on our analyses of previous research, a general workflow was adopted: (a) to identify suitable remotely sensed imagery according to the study area size and spatial resolution requirements; (b) dataset preparation and preprocessing (image calibration, atmospheric correction, samples testing); (c) ancillary data preparation (for some articles); (d) feature classification; (e) output and thematic map production.

In the scientific literature, a wide range of classification methodologies are used, generally grouped in: Spectral MixtureAnalysis (SMA) and Linear SMA (LSMA), vegetation indexes analyses (NDVI, NDBI, IBI), Image Classification (sub-pixel, pixel based, object based, machine learning and deep learning based). A complete overview of such classification methodologies is described by Wang and Li (2019) and not presented here.

For the purpose of the present work such classification methodologies were aggregated in macro-categories to better summarize the differences and approaches for mapping soil sealing. SMA includes standard SMA models and modified methods that helps to identify single and multiple endmembers (i.e. LSMA, MESMA, NSMA, and PNMESMA) (Phinn *et al* 2002, Weng and Lu 2008, Franke *et al* 2009, Li and Wu 2015, Chen and Yu 2016). The Decision/Regression tree category includes Regression trees and Decision Tree methods, but also Random Forest, multiple regression tree, and Support Vector Machine (SVM) (Feng *et al* 2016, Cao *et al* 2018, Fu *et al* 2019). Hereafter, we refer to vegetation indexes as Band Ratio class, by including NDVI, NDBI, MNDISI, SAVI, and others indexes (García and Pérez 2016, Sun *et al* 2017, Gong *et al*

2019, Zhong *et al* 2019). The reclassification process is referred to papers that used ancillary data, for example Land Cover data, to derive soil sealing coverage (Jennings *et al* 2004, Pristeri *et al* 2020). The image interpretation category includes scientific articles that adopted human visual analysis to identify and to map impervious areas (Hartcher and Chowdhury 2017, Lozano *et al* 2019). In some cases human image interpretation might be used in combination with other methodologies (Xiao *et al* 2020). The linear regression category represented the articles that adopted a deterministic equation to estimate soil sealing (Elvidge *et al* 2007). The adoption of linear regression model often is in combination with other techniques (Ma *et al* 2016). Finally, temporal filtering class was always associated with other methods and was usually employed in multitemporal analyses (Zhang and Weng 2016).

1.4. Aims of the research

Firstly, this review article provides a general overview about soil sealing in the period 2000–2020, by analyzing the five main terms adopted in the scientific literature to define the phenomenon. Based on these keywords outcomes, the present works aims to provide a systematic review of remote sensing technologies and methodologies adopted to map and to classify soil sealing, by focusing on the relationships between geographic scales, spatial resolution and classification techniques. Specific aims are to investigate the topic of soil sealing highlighting: (a) the use of the main keywords during 20 years in different countries; (b) the geographic distribution of researches and study cases; (c) the main platforms, methodologies and techniques adopted; (d) relationships among study area size, scales, platforms, resolutions, and classification methodologies; (e) emerging trends and policy implications.

2. Approaches and methodologies for bibliometric analysis

2.1. Review approach

The analyzed papers were selected in the Scopus database within a time-frame of 20 years (last update: 31 December 2020). Search was performed from the Italian territory. The search resulted in 1277 peer-reviewed papers published in international scientific journals. Gray literature was not included in the review, as well as books, proceedings and PhD thesis. The search in Scopus was provided using all the five keywords. Queries were performed in the 'Article Title' and 'Keywords' fields for the Scopus database; only papers in English from 2000 were selected. Indeed, a preliminary analysis showed that before 2000 articles related to soil sealing were limited, less than 2 or 3 per year. Moreover, as reported by Weng (2012), in the 1990s papers on soil sealing defined as impervious surfaces were limited; only in the following years the topic gained interest in the scientific community.

All articles were analyzed to include only papers which (a) focused on the phenomenon of soil sealing and (b) performed mapping and spatial quantification analyses. A total of 503 papers resulted in the selection process and they were then included in the review for detailed analyses. Then, papers were re-analyzed in order to exclude studies not directly related to the topic.

Finally, articles based only on predictive models without any aim of mapping as well as those which used secondary acquired data from other studies were excluded. Therefore, 392 papers are used for the review analysis.

The process of data collection is reported in the flow chart in figure 1.

2.2. Preliminary analysis

Firstly, preliminary analyses were conducted including all the 1277 papers. We therefore performed: (a) frequency and temporal analysis of the five keywords analyzed from 2000 to 2020, (b) country-based geographic distribution analysis at global level of articles which performed soil sealing mapping, and (c) country-based frequency analysis on adopted keywords.

For each article a single keyword was selected and extracted from the 'article title', the 'authors keywords', or the 'indexed keywords' provided by Scopus. The 'indexed keywords' are additional keywords adopted by Scopus to take into account synonyms, various spellings, and plurals of the 'authors keywords' (Scopus 2021).

Identification of countries which more frequently investigated soil sealing is provided by identifying the affiliation of the first author of each article. Subsequently, the ten most frequent countries are selected to identify the frequency of each keyword. Analyses were performed by using Microsoft Excel© and R Studio software.

2.3. Bibliometric analysis and database construction

Bibliometric analysis was performed on a database by designing a standardized data extraction sheet. Articles were analyzed by single authors; subsequently, they were individually cross-checked by the other authors of this study to verify data and extraction. Database was structured into seven main categories: (a) bibliographic references (paper title, author(s), year, issue/volume, journal); (b) goal of the study; (c) location and information on the case(s) study, such as the scope and the size of the case(s) studies; (d) duration analysis of the study (sampling frequencies of temporal images); (e) input data and remote sensors platforms (main input, numbers of sensors of remote sensing platforms, specific category of remote sensing platform, resolution of the input data, and Minimum

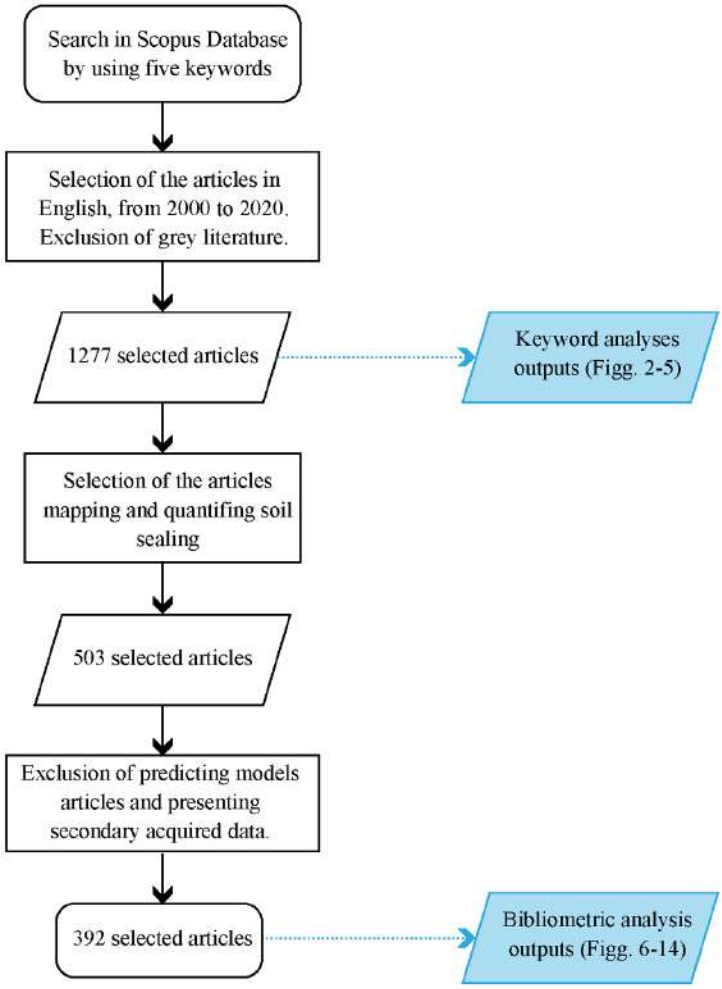

Figure 1. The flow chart illustrates the process of data collection.

Mapping Unit (MMU); (f) classification methodologies; (g) open data and open source software. It is important to highlight that the scope of the study (c) is referred to the definition of the geographical/territorial context in which soil sealing is aimed to be mapped.

All selected criteria are summarized and described in table 1, while a complete overview of table 1 is reported in the supplementary information (available online at stacks.iop.org/ERL/17/053005/mmedia).

Finally, results were analyzed by using R Studio, Microsoft© Excel and the open-source GIS software QGIS (version 3.16).

3. Results and discussion

3.1. Temporal and country-based frequency analyses

Among 1277 analyzed articles, 'impervious surface' is the dominant keyword, with 983 papers adopting this term (76.98%). Other terms present lower occurrences: 'soil sealing' is ranked with 127 occurrences (9.95%), whereas 'land consumption', 'land take', and 'soil consumption' present 65 (5.09%), 53 (4.15%), and 33 (2.58%) occurrences, respectively. See figure 2.

In general, from 2008 soil sealing became a growing research topic from an average of 10–20 papers per year to more than 50 articles in 2008 (figure 3). Later, the number of published papers steadily growths to almost 100 papers in 2015. In the last five years, scientific articles on soil sealing almost doubled, from 100 in 2015 to almost 200 in 2020.

Temporal analysis on keywords show that the dominant term is 'impervious surface' all over the time. Since 2000, it is the first keyword to appear together with 'soil sealing' and it continued to be present until 2020. Since only 2013 a greater variability of adopted keywords is highlighted. Temporal analysis to investigate the occurrences of the five keywords from 2000 to 2020 is shown in figure 3.

Furthermore, we analyzed which country more frequently investigated soil sealing (figure 4). Analysis is performed by identifying the affiliation of the first author of each article. The choice is due to the fact that 79.25% of the articles presented a single country of affiliation for all authors, while 20.75% of the articles presented two different countries. The

Table 1. Database construction: selected criteria, classification and observations. For a complete overview see the supplementary information.

	Database	Description	Observations
(a)	Bibliographic references	Paper title, author(s), year of publication, journal, volume, issue, abstract, keywords, document type (article or review), objective(s) of the study.	
(b)	Goal of the study	Aim of the article, for example if the analysis is providing to assess climate change, water management or urban heat island. We identify 13 categories.	
(c)	Multiple location	Analysis of multiple locations.	
(d)	Dimension of the study area (s)	Study areas size: <50 km^2, 50–100 km^2, 100–500 km^2, 500–1000 km^2, 1000–5000 km^2, 5000–10 000 km^2, 10 000–50 000 km^2, >50 000 km^2.	
(e)	Scope of the study	It is referred to the geographical/territorial context by which the study area was identified. Six categories were therefore aggregated: country, regional, watershed, urban, sub-urban (neighbourhood), and land parcel scale.	Urban scale identifies both a single municipality (i.e. the city of Beijing), but also a county in the USA. This class includes a single municipality and its surrounding urban territory.
(f)	Multi-temporal analysis	Multitemporal analysis or a yearly-based analysis.	Temporal scale
(g)	Duration analysis	Duration of the analysis in year.	Temporal scale
(h)	Sampling frequencies	Numbers of scenes used in the articles.	
(i)	Numbers of sensors	One, two, three or more than three sensors were categorized.	
(j)	Remote sensing platform	Satellite(s) is/are employed for the study. In case of orthophotos we used the category 'airbone sensor'.	In case the article does not employ remote sensing platform we mark the category 'ancillary data' in input data.
(k)	Multiple resolution	Studies based on different images at multiple resolutions.	
(l)	Resolution of remote platform	Maximum and the minimum resolutions were reported in case of multiple resolution images. The aggregated categories are 12: sub-m (<1 m), m (from 1 m up to 9.9 m), 10 m, 10–30 m (from 11 m up to 29.9 m), 30 m, 30–100 m (from 31 m up to 99.9 m), 100 m, 100–250 m (from 101 m up to 249.9 m), 250 m, 500 m, 750 m, 1000 m.	Main sources used for the analysis were considered, excluding images for the data validation or for scaling-up analyses. DMSP/OLS images were considered at 500 m resolution.
(m)	Comparative methodologies	We reported if the study uses comparative approaches, providing a comparison between different methodologies, or if the study uses single methods.	
(n)	Classification methodologies	Sixteen categories were identified and aggregated: Image Interpretation, Image Interpretation and Automated Processing, Band Ratios (e.g. NDVI, Spectral-angle mapper, SAVI, etc), Supervised, Unsupervised, Object-oriented methods (OBIA), ANN methods, Regression trees, Decision trees, Cubist, CART, Random Forest, SVM, SMA, not applicable (N.A.). These categories were summarized in 11 classes.	Regarding both Band Ratio class and SMA category, we reported the specific methods adopted, for example SAVI, NDBI or NSMA, etc, but in the analyses we simplified in the main categories (see the supplementary information to check the detailed classes). Main and secondary methodology(ies) were identified, but we included in the analysis only the main one (see the supplementary information for secondary methods).
(o)	Multiple methodologies	More than one main methods results were included	

(Continued.)

Table 1. (Continued.)

	Database	Description	Observations
(p)	MMU	Declared Minimum Mapping Unit (MMU).	Supplementary information for further details.
(q)	Open data	Three categories were identified: open data, no open data, mixed, not declared (N.D.).	It is referred to the main data used for the analyses, not validation data.
(r)	Open source software	Three categories were identified: open source, no open source, mixed, Not Declared (N.D.).	See the supplementary information for the details.

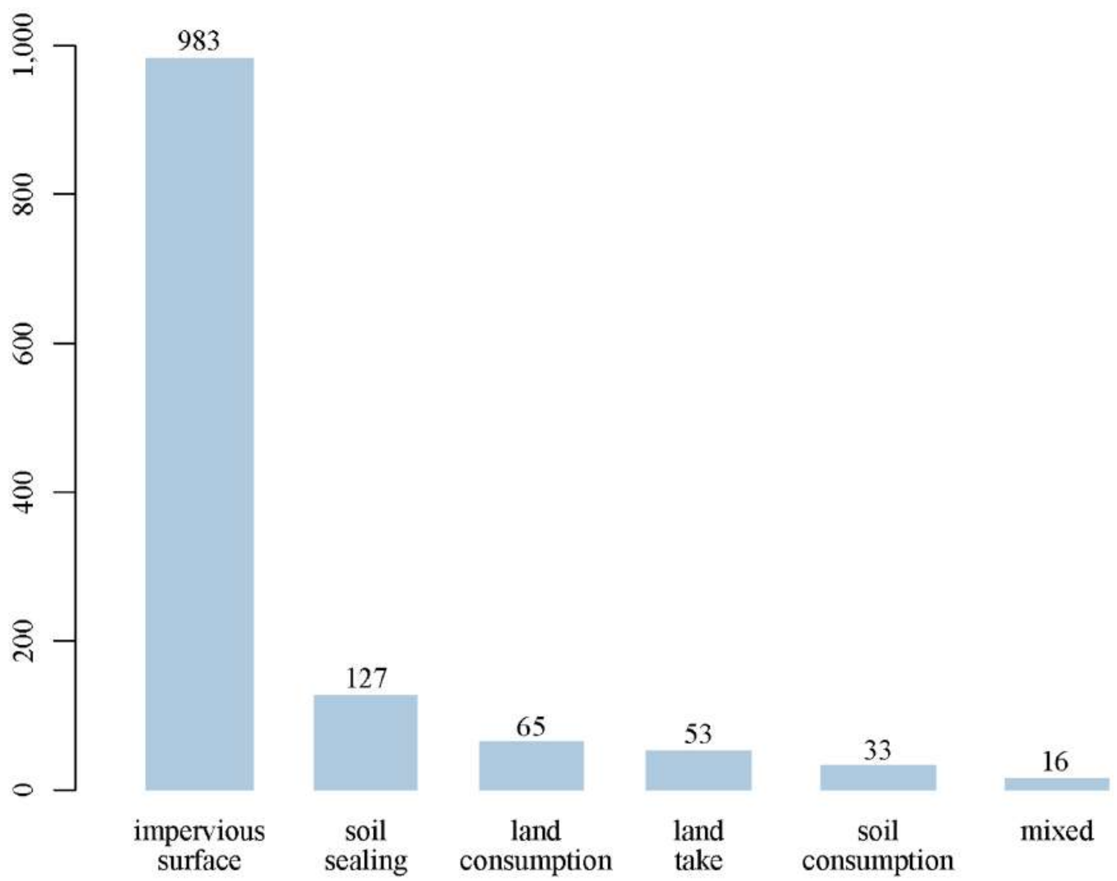

Figure 2. Relative frequency analysis for each of five keywords for all the 1277 articles.

two countries most involved in this topic are the USA and China, with, respectively, 418 (32.73%) and 311 (24.35%) occurrences. Italy is the third country by showing 124 outcomes (9.71%). The other countries represented in the graphs show a drop in the results. It is important to highlights that the 1277 articles a total of 64 countries are covered. Finally, keyword analysis on the first ten countries studying soil sealing are grouped in continental regions (figure 5). Results show that North America present 430 articles using 'impervious surface' definition, avoiding other common keywords. Similarly, Asia adopted this keyword, by total result of 325 occurrences.

In European countries keyword definition for such earth-surface phenomenon is completely different. 'Soil sealing' is the most frequently keyword adopted (72 outcomes); however, it is not completely dominant as 'land take', 'land consumption', and 'impervious surface' are also used (approximately 40 outcomes respectively). 'Soil consumption' is the less adopted keyword (18 outcomes). Finally, Australia and South America show again a preference in the use of 'impervious surface' keyword. Results from analyzing 1277 scientific papers suggests that soil sealing is an increasing topic of interest, mainly driven by North America, Asia and Europe. According to the last decade trend of publications, studies and researches on soil sealing are expected to notably increase in the next years. Moreover, it appears clear a distinction between the definitions adopted in Europe ('soil sealing', 'land take', 'soil consumption', and 'land consumption') and those adopted

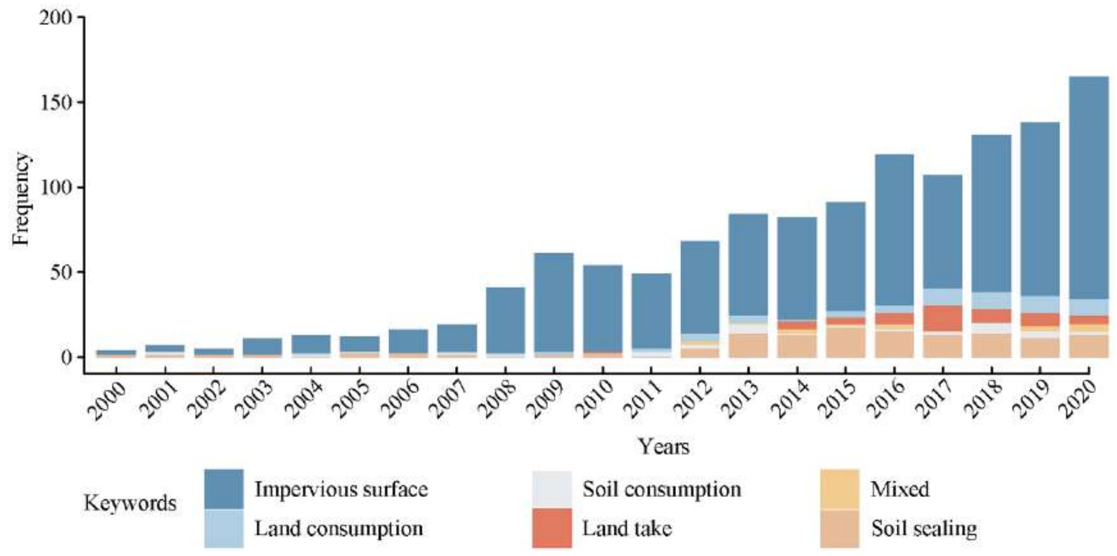

Figure 3. Temporal frequency analysis of the five keywords from 2000 to 2020.

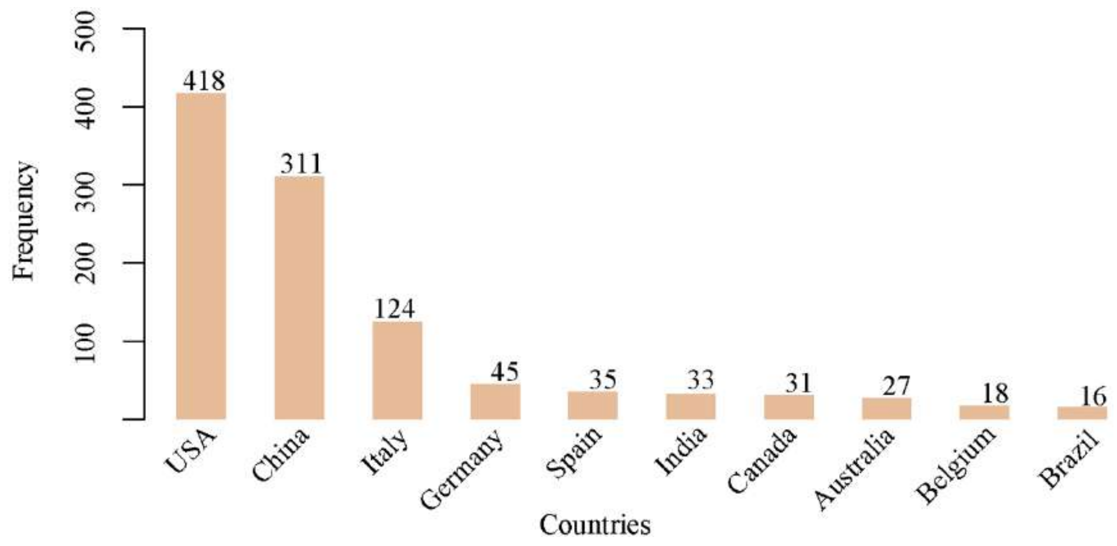

Figure 4. Top ten countries which more frequently investigated soil sealing.

in other continents (mainly 'impervious surface'). This is probably due to the fact that EU made an effort to identify a 'policy and research definition' that involved not only the physical phenomenon of non-infiltration of water into the ground, as evoked by the impervious surface term, but to find a definition which include both the physical process and implications caused by the phenomenon on ecosystems. Thus, since 2002 soil sealing definition is started to be adopted in EU; however, other terms appeared during the years and, still at present, different terms to be employed in academy, in the institutions and among policymakers are making soil sealing definition unclear (Marquard *et al* 2020).

We therefore suggest that at international level, a unique definition should be used in order to avoid contradictions and ambiguities at institutional and policy levels, especially considering strategies and policies to be adopted both to mitigate and compensate soil sealing as well as reducing its impacts on urban ecosystems.

3.2. Geographical distribution of study cases per country

Hereafter, analyses were performed on the 392 papers which mapped and classified soil sealing. The 'country' labeled for each article was based on the study cases and not the affiliation of the authors. It is important to highlight that in this map we considered only defined locations, while global and bioregion study cases were excluded. The two countries showing the majority of the studies are China and the USA (figure 6). China was the country with the most study

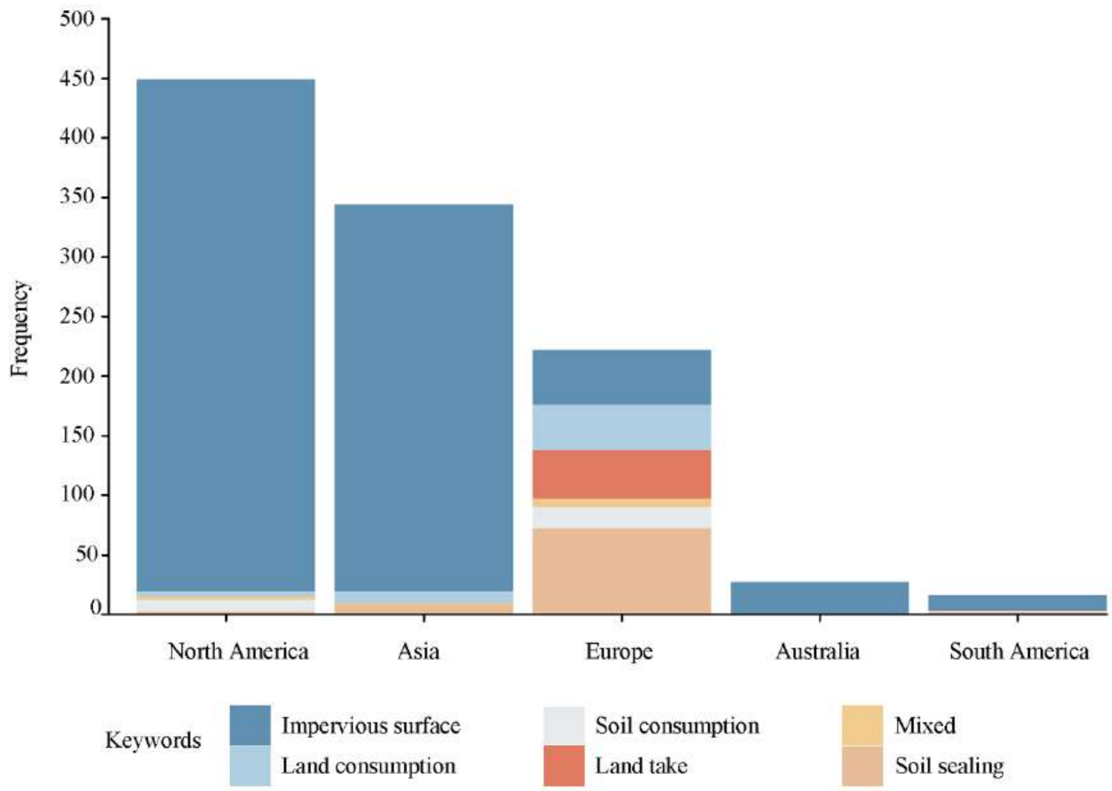

Figure 5. Distribution of keywords for each continental region aggregating the results of the top ten countries which more frequently investigated soil sealing.

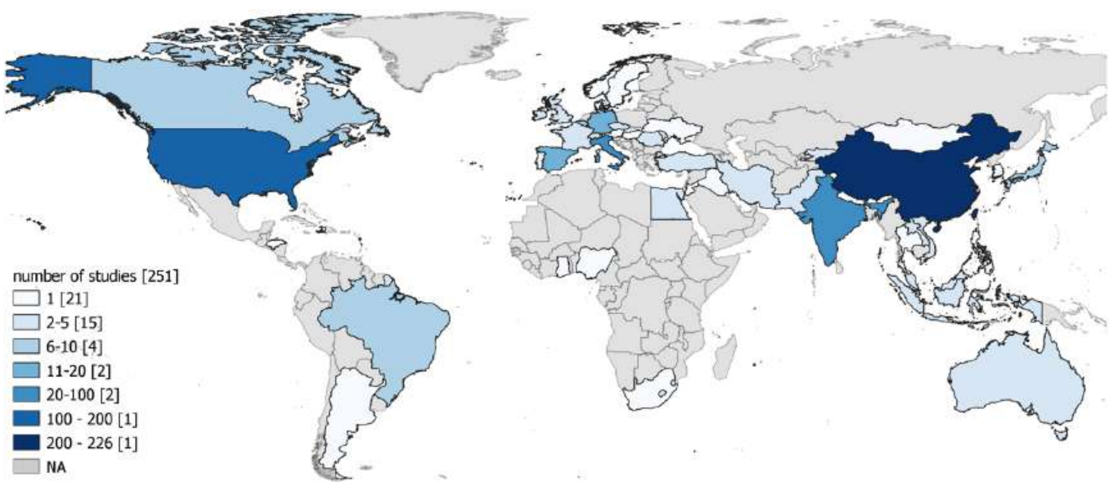

Figure 6. The locations of sites where soil sealing has been studied.

cases, with a total of 226 different articles in cities such as Beijing, Guangzhou, and Shanghai.

The USA was the second most frequently studied country, by showing 138 different study cases. Subsequently, other countries present considerably fewer study sites. Indeed, countries such as India and Italy showed only 24 and 23 study cases, respectively. Other notable countries with an average of ten study cases are the following: Germany, Spain, Brazil, and Canada.

It is worth noting that in big cities in continents such as South America or Africa soil sealing is much less studied probably due to the scarce attention in terms of environmental policies related to urban expansion.

3.3. Scope of the studies

Mapping soil sealing was most often performed at the urban scale, presenting 209 outcomes (figure 7). This scale identifies both a single municipality (i.e.

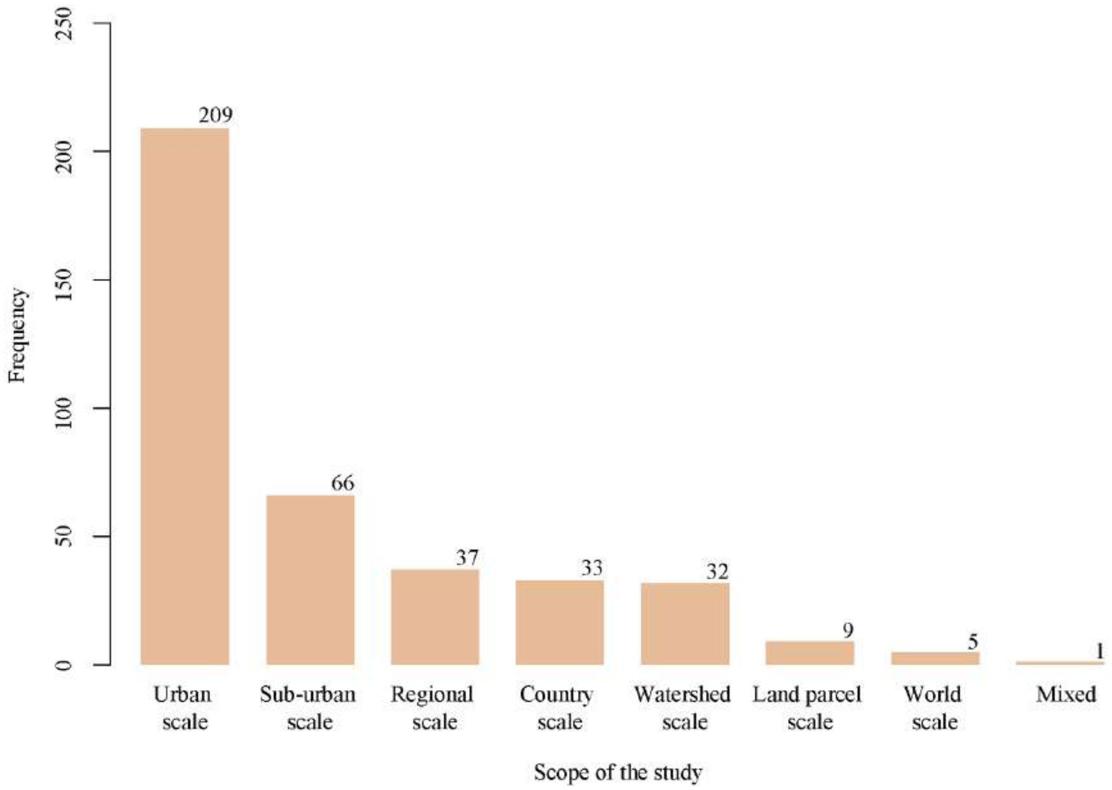

Figure 7. Scope of the study: mapping soil sealing and territorial context of analysis.

Table 2. The eight urban areas most often studied.

Beijing (China)	Guangzhou (China)	Shanghai (China)	Indianapolis (USA)	Nanjing (China)	Wuhan (China)	Hong Kong (China)	Fuzhou (China)
27	21	13	9	8	8	7	6

the whole city of Beijing) as well as spatial analyses performed at county-levels (e.g. in the USA). Moreover, such class also includes those study cases constituted by a single municipality and its surrounding urban territory. The category sub-urban scale presented 67 study sites (16.84%), while regional, country, and watershed classes present similar frequencies, with about 35 findings. Finally, a few studies (9) were performed at the land parcel scale. Only five articles were focused on global scale (Sutton *et al* 2009, Schneider *et al* 2010, Bian *et al* 2019, Kuang 2019, Nowak and Greenfield 2020).

These results indicate that soil sealing is a phenomenon largely related to the expansion of cities and urban areas (Güneralp *et al* 2020) which represent 52.32% of all analyzed papers. Moreover, it is worth noting that the phenomenon was investigated also at sub-urban scales, indicating that small sectors of cities or specific neighborhoods were also studied (Shahtahmassebi *et al* 2016). On the contrary, studies at smaller scales (watershed, regional, and country scale) were less investigated as results highlights a total of 26% of such cases. Studies at a very large scales (land parcel) were only 2.3%, mainly oriented to test specific methodologies or remote sensing data (Im *et al* 2012, Lin *et al* 2019).

Further analysis identified the most studied urban areas (table 2). Seven out of eight are Chinese cities, whereas only one is in the USA. Beijing is the most studied city, followed by Guangzhou and Shanghai. In the USA, Indianapolis is the most investigated city (9), while the second most often studied city is New York (five occurrences). In China, the development and expansion of urban areas was very rapid in the last 20–30 years, following the increase together with economic and urban population growth (Zhao *et al* 2015). Findings in figure 6 and table 2 shows the necessity by Chinese researches for more in-depth urban analyses in order to understand the features, processes, spatial patterns and future development of urbanization (Gu *et al* 2012, Wu *et al* 2014). Such urban studies are often compared to other cities in different countries (Wenhui *et al* 2015). It is also important to highlight that the high number of cities for these two countries are associated with comparative analyses between multiple locations (figure 11).

Explanations for the obvious concentration of study site locations (e.g. by country or city) and scale

Table 3. Relationship between urban scale category and dimension of the study area.

	Total	Percentage
<50 km^2	24	9.13%
50–100 km^2	18	6.84%
100–500 km^2	32	12.17%
500–1000 km^2	26	9.89%
1000–5000 km^2	75	28.90%
5000–10 000 km^2	46	17.49%
10 000–50 000 km^2	34	12.93%
>50 000 km^2	7	2.66%
	263	100%

of analysis are multiple. If the research was funded (or otherwise motivated) by an institution/agency managing the study site, then the explanation was being obvious. In other words, the management need (e.g. to meet a regulatory or policy requirement) for mapping soil sealing promulgated the research study. This explanation could be verified by acknowledgements in the article for the funding or participating entities. The targeted focus of studies on a unique city, such as Indianapolis, may also be attributed to the author's affinity for the city.

Another explanation for the large number of studies focused on cities in China is the availability of research funds from each country. Research funds from the Chinese Academy of Sciences has increased dramatically along with the large increase in the number of remote sensing researchers. This trend of research funds and the number of researchers also occurred in the United States in the 1990s through 2000s. It would be difficult to untangle what the dominant factor (i.e. funding or researcher) is in this relationship but we note this issue is an important explanatory factor in understanding the geographic distribution of study areas.

As the urban scale includes cities of different sizes (i.e. from 100 to 15 000 km^2), highlighting substantial differences in urban territorial context among different countries, we also analyzed relationships with study area size. Table 3 shows the percentage of study area size in urban scale category. The results highlights that urban scale analyses on areas of 1000–5000 km^2 are the most performed (28.90%), followed by 5000–10 000 km^2 dimension of study areas (17.49%).

3.4. Dimension of the study areas and spatial resolution

Firstly, we found that the highest value is represented by areas with a dimension ranging from 1000 to 5000 km^2 (147 occurrences), which is mainly referred as mapping at urban scale (figure 8). The second study areas size are presented by two categories, 100–500 km^2 and <50 km^2: they both present 96 outcomes. Case studies with 500–1000 km^2, 5000–10 000 km^2, 10 000–50 000 km^2 and >50 000 km^2 present similar outcomes, with about 60–70 results.

Figure 8 shows also the relationship between the study area size and the spatial resolution of the remote sensing platforms. Undoubtedly, 30 m category is the most adopted resolution and it corresponds to Landsat satellites. In each study area size category, such satellite platforms are the most employed, with the exception for areas <50 km^2. In some categories of study area size, other resolutions are slightly used; for instance, at 1000–5000 $km^{2,}$ 30 m spatial resolution is overall the 66.67%, while m (1–10 m) and 10–30 m resolution are respectively at is 12.93% and 9.52%. Also at 100–500 km^2, 30 m resolution displays a marked prevalence (50%), whereas m resolution is 21.88% and 10–30 m resolution is 12.50%.

In study areas size <50 km^2, the m resolution is the highest occurrence; while 30 m resolution and sub-m class present less occurrences. Even if, 50–100 km^2 category is usually analyzed at 30 m resolution, it is also studied at m resolution. Finally, >50 000 km^2 shows a comparable result: 30 m class is the most adopted, however 1000 m and 250 m classes display less but similar outcomes.

In the figure 8 study area size classes included in all analyzed papers are reported; it is important to note that 20% of articles analyzes multiple locations, methodology testing or comparative analyses.

The relationship between study area size and spatial resolution is essential to investigate and to accurately map soil sealing. While for large study areas (i.e. 1000–5000 km^2) a medium resolution (30 m) was often adopted, for small areas (<50–100 km^2) high or very-high spatial resolution (sub-m, m or 10 m) images were used. In fact, especially in urban context, geographic features which results in geometry and texture of the urban fabric may vary a lot in size and shape: buildings, roads and parking lots of big cities (>1000 km^2) are generally larger than the same features in medium-small cities (<500 km^2). Hence, in such cases high and very high spatial resolution images are required to detect and extract urban surfaces, minimizing the mixed-pixel effect due to different elements of land cover. On the contrary, for very-large areas (regional, national and continental scales, with areas >50 000 km^2) coarse spatial resolution images are recommended. Finally, a previous analysis between the image resolution, the study area and the resulting MMU is required to avoid under or super-estimation in mapping soil sealing.

3.5. Remote sensing platform and resolutions

The majority of remote sensing platforms are provided by Landsat missions (Landsat 4-5, 7, 8), with 392 outcomes (57.48%) (figure 9). Results show that dataset from Landsat 4-5 are the most adopted with 162 results (23.75%), whereas Landsat

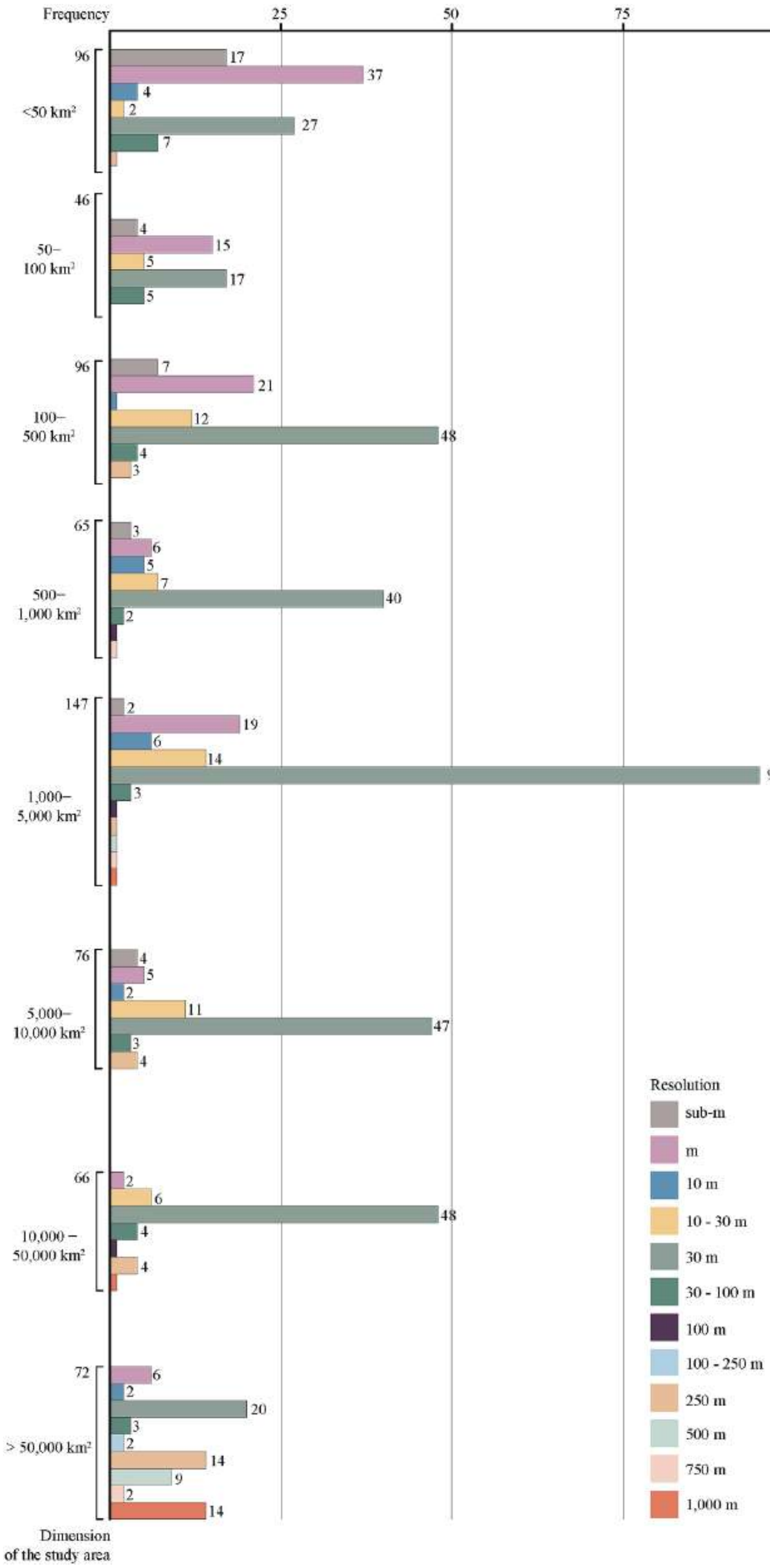

Figure 8. Relation between dimension of the study areas (*x* axis) and resolution (legend). *y* axis shows the frequency of dimension of the study areas.

7 and Landsat 8 present similar outputs. Other platforms show considerably lower results, with less than 40 occurrences. The class 'airborne' is ranked immediately after Landsat platforms highlighting that high resolution images such as orthophotos are still adopted. However, a total of 50 remote sensing platforms were identified in all the analyzed articles, but the majority of them present only one or two occurrences. In figure 9 we represent only platforms with more than ten occurrences.

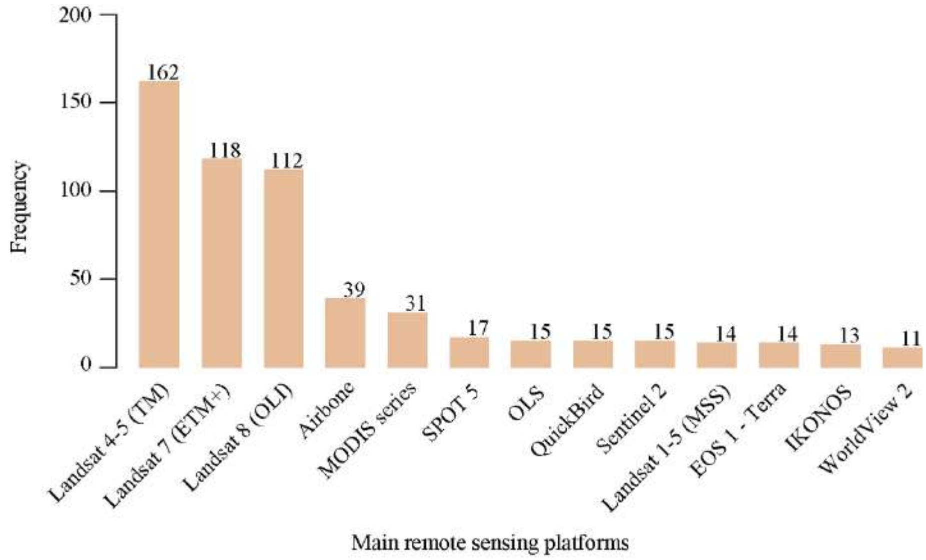

Figure 9. Frequency (y axis) of the main remote sensing platforms (x axis) adopted in scientific papers. The graph shows remote sensing platforms with more than ten occurrences.

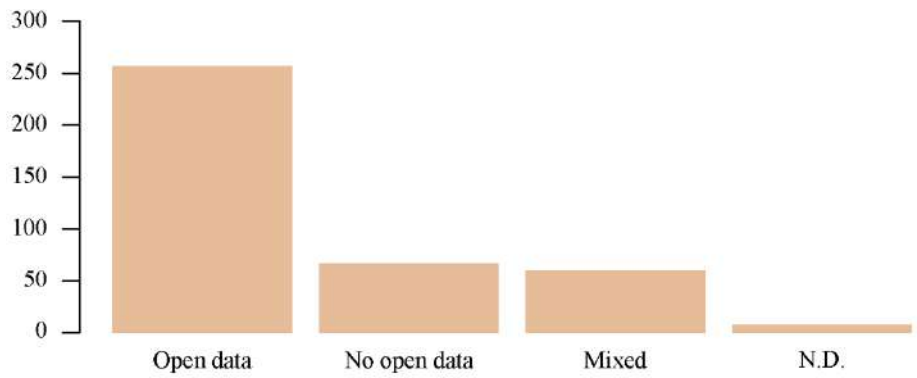

Figure 10. Frequency (y axis) of the use of open data in the scientific papers.

Analysis on the accessibility of adopted spatial dataset show that 65.56% were open data as they are publicly available and free under open license, while 17.09% were proprietary data and 15.31% adopted mixed open/non-open dataset. Proprietary data implies a license by a legal agreement or, more commonly, with cost. In general, studies strongly prefer the use images from Landsat platforms. It is worth noting that the adoption of very high resolution images from optical airborne is relevant, probably due to the fact that orthophotos, often provided by institutions, are generally free access. In general, analyzed papers strongly prefer the use of open public data, consisting primarily of Landsat images as they are also frequently adopted for multi-temporal analyses (48% of studies) (figure 10).

Although since the 2000s the spread of commercial satellite platforms made very high resolution images available and some public agencies such as NASA/USGS and ESA incorporated them into public programs for land-surface monitoring (R J *et al* 2003), soil sealing is still mainly investigated by using open and free data. In many cases, small sample areas from commercial satellites are adopted for validation or accuracy. Moreover, when available, in terms of high spatial resolution and temporal match, Google Earth imageries are used (Lu *et al* 2011, Zhong *et al* 2019). However, their use is still quite limited, probably due to the costs for performing soil sealing mapping in wide areas.

3.6. Multi-temporal analyses

Results on duration of the analyses show that 48.33% of scientific papers performs soil mapping to detect changes over the time, by multi-temporal analyses (figure 11). Yearly-based analyses are more than 51.67% (201 occurrences), while multi-temporal analyses were divided in seven different categories: 41.33% of studies analyzed spatial evolution of soil sealing between 2 and 10 years, 11 and 20 years, and 21 and 30 years, respectively. Within such timeframe categories, 11–20 years of analysis shows the

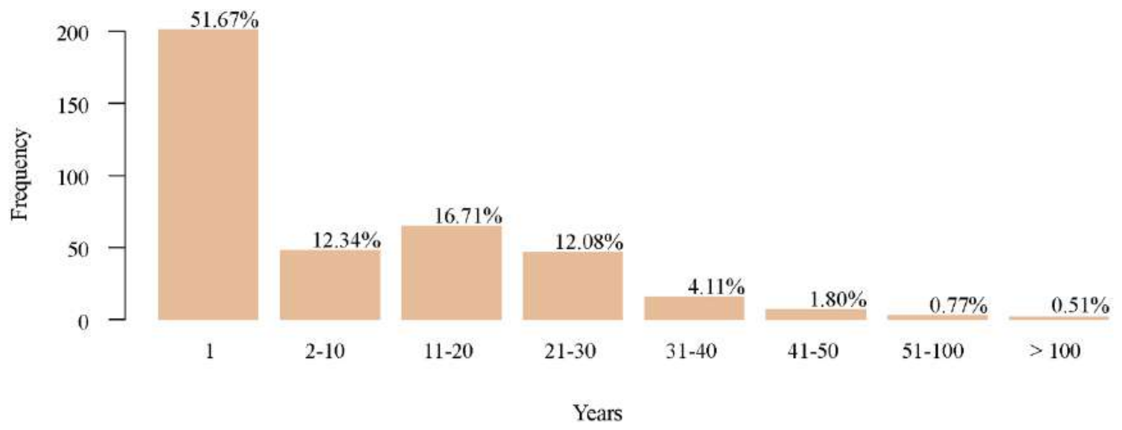

Figure 11. Duration of analyses: multi-temporal analyses and yearly-based analyses.

majority of the results by the 16.71% (65 occurrences), followed by 2–10 years category (12.34%, 48 occurrences) and 21–30 years category (12%, 47 occurrences). Such time frame analyses are feasible as Landsat satellite have a long term frequency in revisiting time.

Long period analyses are scarcely presented. Only 4.11% performed an analysis between 31 and 40 years, while 1.8% between 41 and 50 years. Finally, articles analyzing very long time period (>50 years) are very few (1.28%). The sources adopted in such studies generally do not integrated spacecraft remote sensing technologies but they are based on land cover maps, aerial photographs, and historical maps. For instance, multi-temporal analyses of Rome from 1949 to 2006 were performed by using aerial images and land cover maps (Munafò *et al* 2010); on the other hand, Cortijo investigated the urbanization in Madrid over the last 150 years, by analyzing the historical cartographic sources from topographical maps (2017).

3.7. Main methods to assess soil sealing

In general, the most adopted methodology falls in the SMA category (26.36%; 160 results), following by decision/regression tree class (23.23%), with almost 141 results (table 4). Band Ratio approach is the third one adopted, by the 14.50% (88 occurrences); subsequently, supervised and OBIA classification methodologies presents similar outcomes (45 and 43), while ANN presents 33 results. Image interpretation, Unsupervised classification and Linear Regression show similar results, respectively 26, 22 and 21; Reclassification (18) and Temporal filtering (10) are less adopted to map soil sealing. Globally, 11 different methodologies to assess soil sealing in the reviewed papers were identified. The analysis includes all the main methods used in the articles and it includes both articles adopting single methodologies and articles adopting comparative methodologies or multiple methodologies. On the whole, single methodologies are employed by 293 scientific papers

Table 4. Main methodologies to assess soil sealing. The analysis includes both articles adopting single methodologies and articles adopting comparative or multiple methodologies.

Methodology	Frequency	%
SMA	160	26.36
Decision/Regression tree	141	23.23
Band Ratio	88	14.50
Supervised	45	7.41
OBIA	43	7.08
ANN	33	5.44
Human Image interpretation	26	4.28
Unsupervised	22	3.62
Linear regression	21	3.46
Reclassification	18	2.97
Temporal filtering	10	1.65
	607	100

(75.76%), while comparative approaches are adopted by 99 papers (24.23%). Finally, multiple methodologies are adopted by 62 articles, of which most are single methodologies (72.60%) and the rest are comparative methodologies (27.40%).

Articles assessing comparative methodologies are usually related to different typologies of SMA, such as MESMA, LSMM, and LSMA; they overall correspond to 28.19%. In other studies, comparison of different Band Ratio indexes, such as NDVI, NDBI, and MNDISI are also represented. Such category represents 18.79% of the total. Finally, comparison of different decision/regression tree (for example CART, SVM, and CUBIST) methods correspond to 14.77% of the total (Deng and Wu 2013, Deng and Lin 2020).

In articles assessing multiple methodologies is more complex to identify a main combination of techniques. In most of cases, SMA methods are used as preliminary classification and supervised classification or OBIA are used afterwards (Powell *et al* 2008, Sun *et al* 2020). In addition, other cases show the combination of urban indexes and Linear Regression (Shao and Liu 2014, Ma *et al* 2016).

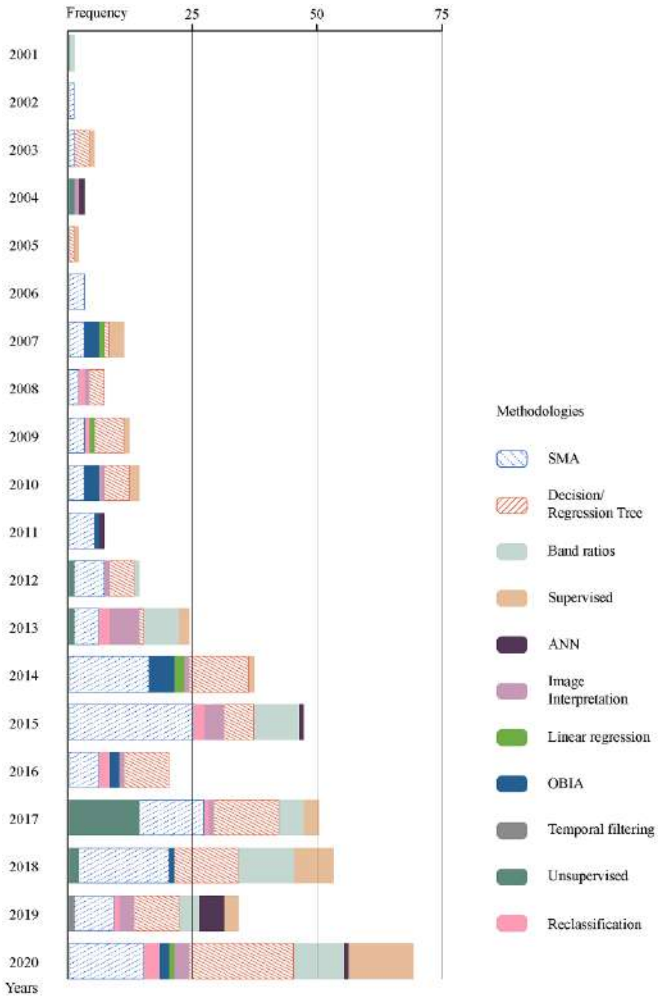

Figure 12. Relationship between main methodologies and year of publication of the articles. In the graph comparative methods and multiple methods are excluded.

To investigate the temporal trend of different methodologies we analyzed the relationship between main methodologies (excluding comparative methods and multiple methods) and year of publication of the article.

Since the beginning of soil sealing analysis, SMA methods and Decision/Regression Tree methods are the most employed (figure 12). SMA was adopted from 2000 and still remains a preferred methodology to map soil sealing when using Landsat-derived dataset, highlighting the need of optimizing the use of 30 m spatial resolution images by spectral mixture and sub-pixel analyses.

From 2017, other methodologies start to be predominant, presenting more than five occurrences per year, and they continue to be present until now. They are Band Ratio and Supervised methods. In 2017 it is important to notice an increase in adopting unsupervised classification methodologies, showing almost 15 results. Figure 13 shows the distribution of the methodologies in relation to the resolution of the remotely sensed images, adopted in each study. The resolution of the studies has been classified taking into account the minimum and maximum resolution used into the analyses. When processing images at high and very high spatial resolution, Image Interpretation, OBIA, Decision/Regression Tree, and Supervised are the preferred approaches; SMA classification is not adopted when using sub-m resolution images. Band Ratio classification methodologies start to be used from 10 m image resolution, while it plays a relevant role at 30 m pixel size, together with Supervised, Decision/Regression Tree, and SMA techniques. The latter two approaches are the most adopted at 30 m resolution, by the 13.53% and 25.08% respectively (41 and 76 outcomes). Finally, a comprehensive overview is given by analyzing the relationships between methodologies, image resolutions, and study area size. This output proposes a relational framework to link the main geographic components to remote sensing models and methodologies for mapping soil sealing. Relationships among the three categorical variables are shown in the graphical summary (figure 14). The majority of the results are located in the range of 30 m resolution and 1000–5000 km^2

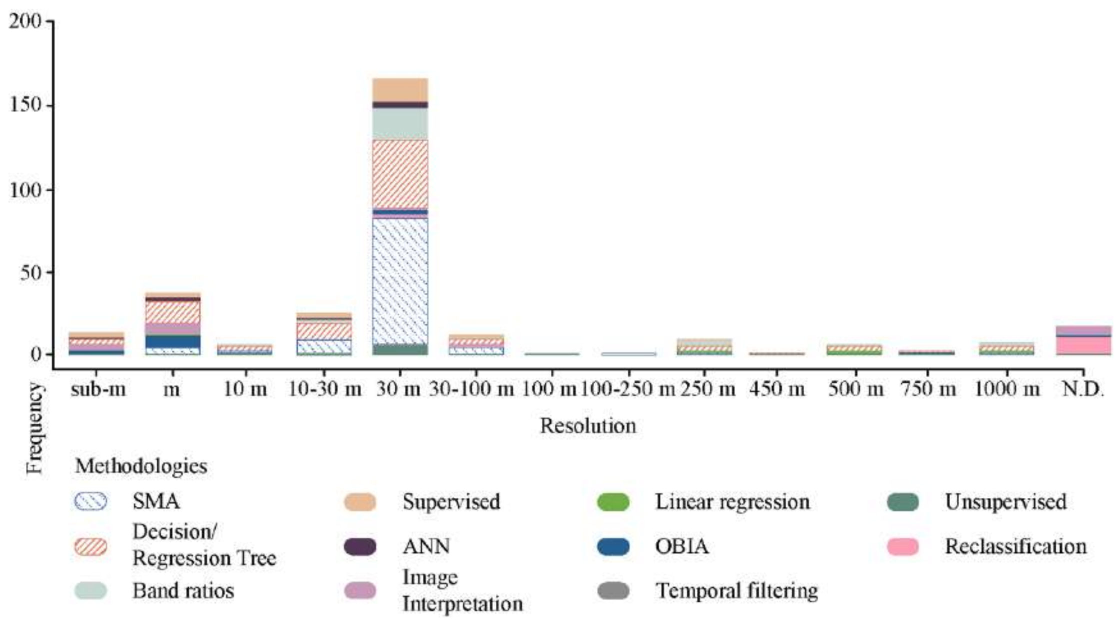

Figure 13. Distribution of methodologies (legend) in relation to the spatial resolution (*x* axis) of remotely sensed images. In *y* axis is reported the frequency of the resolutions.

by adopting three different approaches: SMA (47 outcomes), Decision/Regression Tree (21 outcomes), and Band Ratio (8 outcomes). At 30 m resolution, also the category 5000–10 000 km^2 is well represented by SMA (27 outcomes) and Decision/Regression tree (8 outcomes). For mid and small size study areas (from <50 km^2 to 50–100 km^2) images at 1 m spatial resolution are used, following by 10–30 m pixel size, mainly used by Image Interpretation and Decision/Regression Tree. Image spatial resolution of 30 m and 30–100 m are used to perform Unsupervised and Band Ratio land cover classification. On the contrary, for very large study areas (10 000–50 000 km^2 and >50 000 km^2) the preferred resolution is 30 m and the methodologies mostly adopted are Band Ratio, Decision/Regression Tree, and SMA. Finally, coarse image resolution is scarcely adopted for mapping soil sealing and they are acquired only for very large dimension of study areas. In these cases, at 1000 m image resolution, SMA methods are used, while at 250 m it can be identified also Band Ratio and Decision/Regression tree. Generally, they are adopted all for large-scale study areas, at continental and global scale.

Results with less than two outcomes are not represented in figure 14; moreover, we included both single and comparative methodologies, but we exclude articles with multiple methodologies.

3.8. Mapping soil sealing: an issue of scale and resolution

An applied research approach to map soil sealing requires accurate features extraction and usable output for monitoring and controlling the phenomenon.

Undoubtedly, relationship between the nominal spatial resolution of remotely sensed images and the scale of analysis is a crucial point that must be considered in soil sealing mapping, feature extraction and spatial analyses. The higher the spatial resolution of the image, the more detail can be detected from the analyzed surface.

In contrast to forests or agricultural landscapes which generally presents more uniform spatial patterns, most of city surfaces are heterogeneous as a result of a mash-up different geographic features which typically compose an urban fabric. Sealed urban surfaces are generally represented by areal (buildings and parking lots) and linear (roads and streets) features. According to the different analyzed papers, geometric and spectral characteristics as well as features size of urban surface features vary a lot, making relationships between scales and resolution crucial for mapping soil sealing by remotely sensed data modelling (Weng 2014). A geographical approach to scale and resolution might help to better clarify such relationships. Firstly, the geographic scale (or observational scale) refers to the size or the spatial extent of the study on which analyses are performed (Quattrocchi and Goodchild 1997); it usually corresponds to the declared study area. As reported in our review analyses, the geographic scale might range in different order of magnitude, accordingly to the analyzed context (table 4, figures 8 and 14). Secondly, as quantitative analyses are often pursued, the measurement scale should be strongly investigated, as it represents the nominal resolution—namely spatial resolution—of the remotely sensed images (Quattrocchi and Goodchild 1997). As showed in our comparative analyses, important differences in image

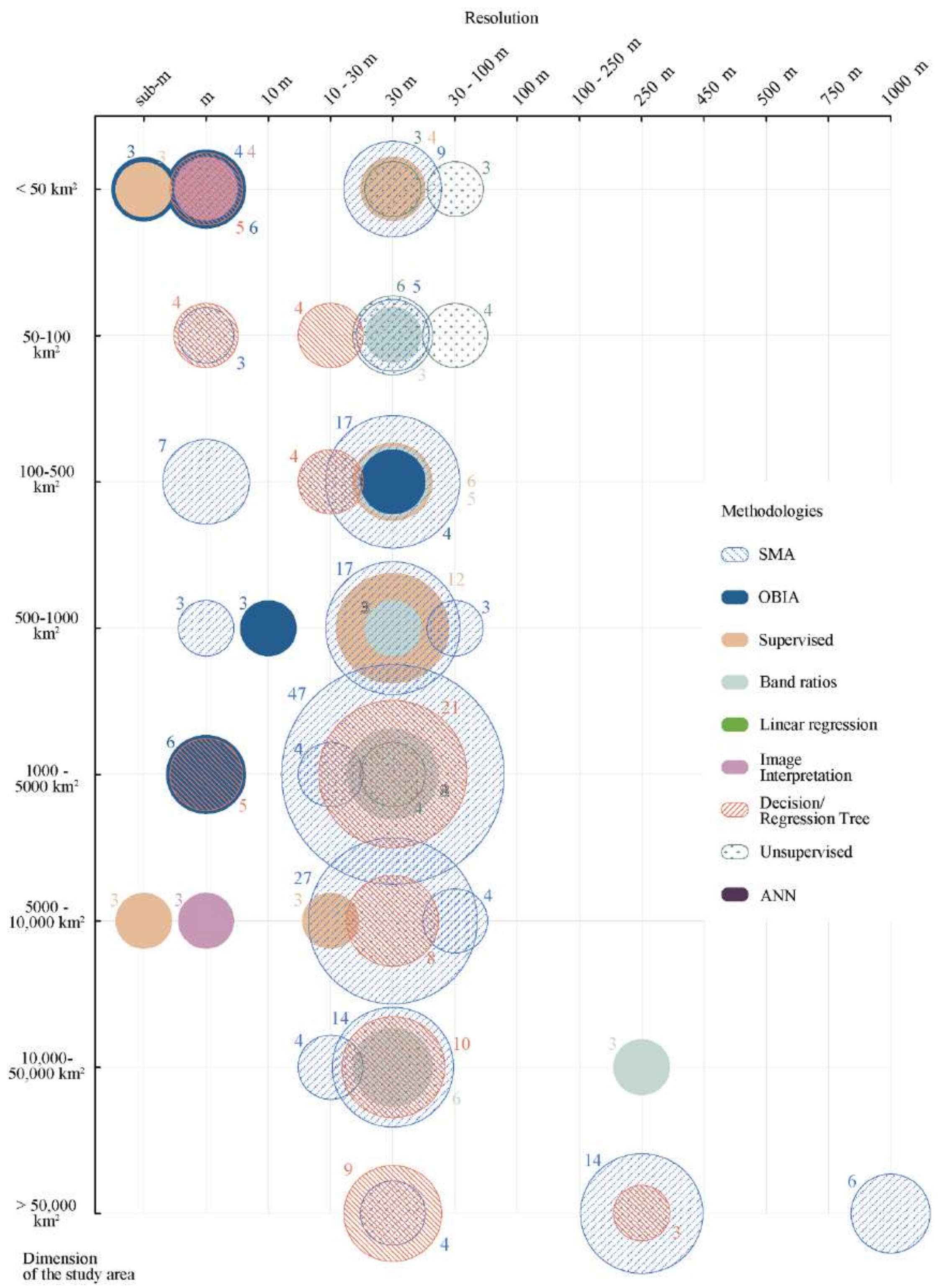

Figure 14. Relation between methodologies (legend), resolutions (y axis), and dimension of the study areas (x axis). The diameter of the bubbles indicates the frequency of the methodology used.

resolution are reported to map soil sealing in a wide range of study area size (figure 8).

In fact, the spatial resolution is related to smallest picture element which represent its spatial footprint on the ground and, therefore, the size of the smallest detectable feature. Theoretically, only features larger than one pixel can be detectable. Indeed, by considering both geographic scale and image resolution, a MMU—defined as 'the smallest size areal entity to be mapped as a discrete entity'—for feature to be detected should be analyzed and identified (Lillesand and Kiefer 1994). However, it is generally agreed that the smallest feature that can reliably be mapped would need to fall at least 2 × 2 or 3 × 3 contiguous pixels in size, by defining a suitable MMU (Saura 2002, Álvarez 2017). The adoption of a certain MMU that is appropriate for a specific land use extraction and classification is therefore paramount as an earth surface phenomenon detectable on one given geographical scale may not exist in another one, due to the effect of spatial resolution. Mapping and classification accuracy of urban surfaces is therefore dependent on the MMU capable to detect different sizes and geometries of land cover. Hence, to accurately detect and to discriminate sealed urban surfaces such as buildings, parking lots, pavements and roads width, a spatial resolution ranging from 0.25 to 1 m pixel size is strongly recommended (Jensen and Cowen 1999, Franklin *et al* 2003, Rogan and Chen 2004).

In general, remote sensing sensors equipped on aerial platforms (satellites, airplanes and drones) acquire images in a wide range of spatial resolution. Even if classification of spatial resolution is changing over time due to the advances in sensor technology and computing capacity, it can be currently categorized in four main classes: coarse (>1000 m), medium (100–1000 m), high (5–100 m), very high (<5 m) (Liang and Wang 2019). Coarse spatial resolution images are scarcely suitable for mapping soil sealing, with the exception of mapping at global scale; medium resolution images such as MODIS (250–1000 m) and NOAA-VIIRS (750 m) dataset are usually adopted for mapping at small scale (national, macro-regional, continental regions, world-scale); high resolution such as Landsat 8 (30 m) and Sentinel 2A/B (10 m) is commonly used for mapping at regional and local scale; very high spatial resolution such as images from Pléiades Neo airbus, from the Space Agency of France (0.3 m), from commercial satellites, from WorldView (0.3 m), and ortophotos generated from airborne optical sensors are used for mapping at large and very large scale (urban, suburban, neighbourhood scale) (Weng 2012, Asad *et al* 2017, Wang and Li 2019, Radočaj *et al* 2020). A complete overview of main satellite platforms, including spatial and spectral resolution, is presented by Sam Navin and Agilandeeswari (2020).

3.9. Goals and policy implications of the studies

An objective of the present work is also to investigate which studies were performed as applied research for mapping soil sealing or to highlight some policy implications for sustainable territory management or spatial urban planning. Results show that almost 90% of the analyzed studies focused on merely techniques testing and performances, on efficiency of feature extraction or on study case comparison. Moreover, different articles were more oriented to more specific purposes, for example identification of urban heat islands or assessment of hydraulic drainage, by performing soil sealing mapping as preliminary analysis (Xu 2010, Coseo and Larsen 2019, Siddiqui *et al* 2021). In general, the majority of the studies does not present direct or indirect links to urban policies and strategies. Only about 10% of the articles resulted in outcomes as scientific support to policymakers and stakeholders to pursuit sustainable urban development. In such articles, an important section is dedicated to quantify soil sealing with the purpose of supporting territory planning.

In our opinion, in order to improve urban sustainability tools and knowledge, scientific studies on soil sealing should have a strongest applied dimension and should better respond to the international calls from UN SDGs as well as from the 'Zero net land take 2050' Strategy and the 'EU soil strategy for 2030' of European Commission (2011), (2021), Department of Economic and Social Affairs of United Nations (2015). Indeed, these researches will be essential especially for the management and improvement of urban ecosystems, as they are estimated to increase well beyond than 50% of global population in 2050.

Moreover, due to this gap, methodologies and techniques for soil sealing mapping are missing from urban plans and strategies making monitoring soil-related ecosystem services still unexplored (Lam and Conway 2018, Teixeira da Silva *et al* 2018, Calzolari *et al* 2020). Even if some urban plans are framed on this concept, indicators and actions to monitor soil sealing and soil-related ecosystem services are almost absent, highlighting how city planners and designers are still far from a concept of soil as a natural resource to preserve and maintain. In fact, soil sealing is usually not related to the multiple ecological effects, at different scales. For this reason, the role of scientific community of producing applied research on soil sealing more connected to international and national policies would be fundamental to fill the gap.

3.10. Emerging trends

In future researches, studies should take in a more consideration a set of essential criteria for soil sealing analyses which can considerable affect the methodological choice: the scope of the study, the scale of analysis, the urban fabric of the study case as well as the spatial resolution of remote sensed images. In addition, availability open and free access data can be crucial elements to be considered for future researches. Hence, Landsat images will surely remain the most used also for their potential to provide a historical series; on the other hand, concerning Sentinel images more time will be necessary to use them in diachronic studies of soil sealing, even though they offer higher spatial resolution (10 m pixel size).

In fact, new imageries available in 2022 from Landsat 9 mission (launched in September 2021), by maintaining the same spatial resolution of its spectral bands, will allow the comparison between different years, confirming that NASA/USGS constellation is the 'longest, running, continuously operating Earth observation satellite program' (Masek *et al*

2020). Moreover, Landsat satellite missions provide open data to their users, unlike other satellites that are mostly commercial satellites. In the next future, also Copernicus Sentinel-2, which is based on a constellation of two satellites, launched in 2015 and 2017 respectively, will be an important silos of spatial data for monitoring urban environment, not only for its high temporal frequency (revisit time of 10 d) and for its open access dataset (Misra *et al* 2020). Our results show that only 15 studies used Sentinel-2 imageries, indicating it is still not widely adopted for mapping soil sealing. However, it is worth noting that European Union is adopting these platforms since 2015 to monitor the trend of the phenomenon in all European countries (European Environment Agency 2018).

In perspective, the development of platforms for Big Earth Data management and analysis, i.e. Google Earth Engine and Sentinel Hub, might provide important advancements in soil sealing mapping and analyses. In fact, these platforms might represent an important support to researchers to store, process, disseminate and analyze big geospatial data (Gomes *et al* 2020).

Although an increasing availability of economically accessible very high resolution images is expected in the near future, automatic methodologies to accurately map soil sealing will be constrained by the study area size. In fact, study area size of different urban context may range in different order of magnitude (table 3 and figure 8). In general, for area size smaller than 1000 km^2, higher spatial resolution images combined with automatic methodologies (Supervised, OBIA, ANN) might provide promising results, by increasing mapping accuracy; however, for area size greater than 1000 km^2 automatic methodologies to extract sealed features will be strongly limited by computing resources. Hence, SMA and Decision/Regression Tree methodologies will be probably still adopted to perform soil sealing mapping on high image resolution (5–100 m).

Finally, although in Africa and South America articles about soil sealing are at present limited, an increase of applied researches for mapping and monitoring the phenomenon in those urban contexts is expected in the future.

4. Conclusions

Soil sealing is one of the main environmental issues of our decade. This topic is of great interest not only from a scientific perspective but also for policymaking for soil protection and sustainable development at local, regional, national, and international level. Our systematic review focused on studies approaching the phenomenon by using quantitative methodologies, by analyzing the extension and the amount of soil sealing and investigating the spatial evolution of the phenomenon over years.

In general, soil sealing mapping requires a preliminary assessment among the study area size, the image spatial resolution and the scale of analysis. These elements are crucial for identifying the most performative classification methodologies. Furthermore, they are essential to accomplish with applied research oriented both on controlling and limiting the phenomenon through policy implementation.

In scientific literature, terms to define this specific form of land use change are still heterogeneous, highlighting the need to identify a unique and shared definition, not only in European context, but also at international level. In fact, in cities and urban areas monitoring soil sealing is essential to identify concrete pathways for protecting soil functions and services. Hence, academic research should be more oriented to urban policies in order to support and implement ecosystem services required to human well-being and health, ensuring, within cities, adequate permeable areas, such as green areas and agricultural lands (Maes *et al* 2019).

Both standardized monitoring systems and strategies/policies harmonization between different countries are crucial in order to reduce and limit soil sealing and to straightaway contrast local effects of climate change (Aragón-Durand *et al* 2014, Decoville and Schneider 2016).

The effort provided in this review is to go beyond a national perspective and to strengthen a more global view, seeking to tackle this complex phenomenon with exchanging knowledge and experiences and fostering the communication on this topic.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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