The changing faces of soil organic matter research

P. SMITH[A], S. LUTFALLA[B,], W.J. RILEY[C], M.S. TORN[C], M.W.I. SCHMIDT[D] & J.-F. SOUSSANA[B]

[a]Institute of Biological & Environmental Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen, AB24 3UU, UK, [b]Institut National de la Recherche Agronomique (INRA), 147 rue de l'Université 75338 Paris Cedex 07, France, [c]Earth and Environmental Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA, and [d]Department of Geography, University of Zurich & University of Zurich Research Priority Program Global Change and Biodiversity (URPP GCB), 8057 Zurich, Switzerland.

Correspondence: P. Smith. E-mail: pete.smith@abdn.ac.uk.

Running title: The changing faces of soil organic matter research

Summary

For the 70th Anniversary of the establishment of the British Society of Soil Science, this short paper explores the idea that research on soil organic matter has remained a central theme within soil science over the past 70 years, albeit with changing emphasis and application. The number of publications on soil organic matter has increased greatly in recent decades; for example there were almost 35 000 journal papers with this theme in the decade 2007–2016. Several topics in research on soil organic matter, such as soil fertility, have endured for a number of decades, with publications found on soil organic matter and fertility in the decade 1947–1956. A search with other keywords occurring with soil such as climate change, biodiversity, fertility, quality, health and security showed that several topics did not appear before the 1970s and 1980s, but since then the sub-topics and applications have diversified. Carbon is a keyword that has become more associated with publications on soil organic matter; carbon is in over half of soil organic matter publications of the last decade. A closer examination of research on agricultural soil carbon sequestration since 1990 reveals that the focus of papers in the literature has changed over this period. A closer examination of papers on modelling shows that the next generation of soil organic matter models is developing from pseudo first-order decay models using conceptual pools and prescribed controls of turnover time to vertically resolved, microbially explicit models, representing mineral surface and plant interactions. Given its higher policy profile during the last two years, research on soil organic matter and soil carbon sequestration is predicted to have a bright future.

Keywords: soil organic carbon, sequestration, climate change, biodiversity, soil fertility, soil quality, soil health, soil security

Highlights

- The number of publications on soil organic matter has increased greatly in recent decades
- Soil fertility research has endured for many decades, whereas other topics have diversified
- Soil organic matter has been increasingly associated with carbon, which has changed the focus of papers since 1990
- Expanding policy attention to soil organic matter research during the last two years suggests a bright future

Introduction

During the 70th Anniversary (2017) of the British Society of Soil Science (BSSS), we examine the changing emphasis in research on soil organic matter in the 70 years since BSSS was established, and we explore more closely how research on agricultural soil carbon sequestration has changed since 1990. The study was inspired, in part, by a meeting of one of the authors, PS, during the 1990s with a veteran soil scientist, Dr John M. Kimble, who worked for the US Department of Agriculture (USDA), during the establishment of a soil organic matter network, SOMNET (Smith *et al.*, 1996; Smith *et al.*, 2001; Smith *et al.*, 2002).

Professor David Powlson at Rothamsted Research led SOMNET (Powlson *et al.*, 1998), which was established to collect together information (meta-data) and where possible, actual data, on long-term soil organic matter experiments from around the world. The goal was to establish a network so that we could learn collectively from the experiments, and to test models of the dynamics of soil organic matter under a wide range of different conditions (Smith *et al.*, 1997). This work was all done at a time before it was possible to obtain data online. Therefore, all the material was collected by paper questionnaires and typed into the database manually; younger soil scientists are now able to move data around freely but with the potential for data overload.

Dr Kimble had been doing research on soil organic matter (SOM) for some time and had co-edited a range of books on the subject in the Advances in Soil Science series (e.g. Lal *et al.*, 1995). During one SOMNET meeting, he noted that although his main focus had been on soil organic matter for many years, the reasons for the research had changed. For example, at first the aim was to provide information to support agronomy, then to improve soil fertility, and then (in the 1990s) to combat climate change. It is striking from this observation (i) how universally important soil organic matter cycling is for a multitude of issues and (ii) how we, as researchers, need to be adept at adapting our work to the demands and interest of those who provide short-term funding.

Twenty years after publishing the first outcomes of SOMNET (Smith *et al.*, 1997), Dr Kimble's comments in the 1990s about the changing requirements in research on SOM remain true today. In this paper, we examine topics of research that come under the banner of soil organic matter, and how these have changed over the decades. Our aim here is not to provide a comprehensive and detailed review of all soil organic matter research, but simply to examine new applications for our science over the years, examine how the emphasis has changed in agricultural soil carbon sequestration research since 1990, and to outline some recent advances in soil organic matter modelling.

Materials and methods

For the first part of our study, an analysis of changing topics in soil organic matter research over the last seven decades, a Web of Knowledge search was done on 15 December 2016 using the following search terms: “soil AND organic AND matter”, then repeating the search six further times with the additional terms AND “climate”, “biodiversity”, “fertility”, “health”, “quality” and “security”. To determine how the prominence of these topics has changed over the years, for each search the periods of time were restricted to decades. The following decades were examined: 1947–1956, 1957–1966, 1967–1976, 1977–1986, 1987–1996, 1997–2006, and 2007–2016. The fact that some soil organic matter research could have been published with other terminology, for example “soil organic carbon”, was not considered because the purpose of the investigation was to determine trends over time, rather than to provide a comprehensive record of all papers on the topic. For all decades except for 1947–1956, an additional analysis was performed to determine the proportion of soil organic matter publications that also mentioned the term “carbon”. This was achieved by performing a search on the Web of Science (core collection) on 4 April 2017 and comparing the number of results from the query “soil* AND organic AND matter AND carbon” and of the query “soil* AND organic AND matter”. Because the number of publications that focus on soil organic matter have increased greatly over the decades (see Results and discussion), the results for sub-topics have been standardized by expressing them as a proportion of all papers published on soil organic matter during the same decade.

For the second part of our study, to examine the changing emphasis of research on agricultural soil carbon sequestration since 1990, we performed the following search on the Web of Science (core collection) on 5 January 2017. Topic: ((soil* OR land) AND organic AND carbon AND (storage OR sequestration) AND (agriculture* OR crop* OR rangeland* OR arable OR pasture* OR cultivation OR cattle OR sheep)). Time periods were 1991–2002, and 2016. Keyword density maps were produced using the VOS viewer (www.vosviewer.com).

Results and discussion

Research papers on soil organic matter have increased rapidly over the decades

Journal papers on soil organic matter have increased greatly over the decades; there were fewer than 60 papers on the Web of Knowledge for the decades 1947–1956 and 1957–1966, whereas this increased to almost 35 000 over the last decade, 2007–2016 (Figure 1). This change partly reflects the greater number of publications held on the Web of Knowledge, with the result that recent decades are represented more thoroughly and are associated with the rapid growth in the number of journals and papers in science more generally. For agricultural soil carbon sequestration, the number of papers increased greatly between 1990 and 2016 (Figure 2), with papers on soil carbon sequestration published in journals on a variety of disciplines (Figure 3).

Trends among topics in soil organic matter research

The trends among subtopics over the past seven decades are shown in the six panels of Figure 4. Among the subtopics examined, soil organic matter and fertility has been studied for the longest period; papers on this subtopic appeared as early as the decade

1947–1956. The first papers on soil organic matter and quality appeared during 1967–1976. Papers that showed the association between soil organic matter and climate, biodiversity, health, and security began to appear in the decade 1987–1996. In the most recent decade, soil "quality" was the most prominent subtopic; it accounted for ~19% of all papers on soil organic matter, followed by climate with ~14% of papers. Fertility remains a key subtopic seven decades after the first papers identified on this topic in our study were published; it accounts for over 7% of all papers on soil organic matter in the last decade. Biodiversity, health and security feature in 2, 3, and 1% of papers, respectively, of soil organic matter publications during the last decade (Figure 4).

Evolution of the occurrence of the term "carbon" in soil organic matter publications shows a strong increase over time: during 1957–1966, less than 9% of the papers on soil organic matter mentioned this keyword compared to 51% in the decade 2007–2016 (Table 1). The regular increase in this proportion started during the period 1987–1996, and perhaps shows recognition of the importance of soil carbon, as part of organic matter, in the global carbon cycle. However, this could also reflect a change in method for measuring soil organic matter or carbon content from loss on ignition to C and N analysers using dry-combustion.

Considering publications on agricultural soil carbon sequestration, Figure 5 shows the keyword density map of publications from 1991–2002 (Figure 5a), and those published in 2016 (Figure 5b). During the period 1991–2002, nitrogen was at the centre of a single keyword cluster, with grassland, decomposition, great-plains, management and grassland soils also featuring prominently (Figure 5a). In 2016, there are more keyword clusters, with the most prominent centred on sequestration, management, matter and climate change, and others centred around organic matter, carbon sequestration, and another on nitrogen-storage (Figure 5b).

This simple analysis of the soil organic matter literature corroborates the endurance of research on soil organic matter over the past 70 years. It also confirms that some topics, such as soil fertility, have been studied for many years and continue to be relevant, and remain a subject of intense study. The analysis also shows a diversification in the topics to which soil organic matter is relevant over the last three decades, with, for example papers on soil biodiversity, soil health, climate change and soil security. Since 1991, the keyword analysis of publications shows that the focus of agricultural soil carbon sequestration has also changed over the last 25 years. Topics that have increased in prominence recently include soil microbiology, biology and ecology, with metagenomics of soils (not shown) becoming more prominent very recently; see for example the recent 'Landmark' papers in this journal (Nannipieri *et al*., 2017; Blagodatskaya *et al*., 2017).

The next generation of soil organic matter models

Papers on soil organic matter modelling have also become more prominent (Figure 5b). Over the past few decades, tens of soil organic matter models have been developed (Stockmann *et al*., 2013), yet their predictive capability at spatial scales that interact with climate remains poor (Bradford *et al*., 2016; He *et al*., 2016; Todd-Brown *et al*., 2013). In spite of this long period of development, the conceptual diversity that SOM models span falls broadly into only two categories: First, traditional pseudo first-order decay approaches with a range of SOM pools and controls on turnover times and decomposition pathways, e.g. Century (Parton *et al*.,

1987) and RothC (Jenkinson & Coleman, 2008). Second, more recently, explicit microbial models, some with representations of mineral–surface interactions, vertical transport, nutrient controls and plant interactions (e.g. Ahrens *et al*., 2015; Allison *et al*., 2010; Grant, 2013; Manzoni *et al*., 2014; Riley *et al*., 2014; Wang *et al*., 2013; Wieder *et al*., 2015; Wieder *et al*., 2014). The pseudo first-order decay approaches rely on prescribed soil organic matter turnover times that are inferred from organic carbon stock at the site level, laboratory incubations, litter bag studies, and sometimes isotopic or flux observations, or both. These models have recently been shown to have very large parameter equifinality (i.e. different input parameters produce the same effect), which has been hypothesized to result from incomplete representation of the processes (Luo *et al*., 2017; Luo *et al*., 2015; Tang & Zhuang, 2008). Although the debate about whether more explicit process representations lead to more accurate predictions remains unresolved, there are clearly some processes for which the traditional models are unsuited and microbially-explicit representations are needed; e.g., soil priming (Georgiou *et al*., 2015), mortality (Georgiou *et al*., 2017), leaching and stabilization of dissolved organic carbon, DOC (Dwivedi *et al*., 2017).

In addition to the focus on soil organic matter content and dynamics, the community studying pesticide dynamics and residues is actively formulating model structures to account for pesticide transformation and stabilization (Kästner *et al.*, 2014). Although most of that focus has been on non-extractable pesticide residues, some recent research has also been involved in developing models to represent the interaction of pesticide residues with biologically-derived soil organic matter, with model structures similar to those in ongoing ecosystem modelling research focused on SOM stocks.

Prospects for soil organic matter research in the future

The longevity of soil organic matter research is borne out by the continued demand for long-term experimental data on soil organic matter dynamics (Richter *et al.*, 2007; Sándor *et al.*, 2016). Although the funding for SOMNET ceased in the early 2000s, its legacy continues with the data being based first as the Long Term Soil Experiment (LTSE) network run from Duke University, Durham, North Carolina in the USA (Richter *et al.*, 2007), and now hosted by the International Soil Carbon Network (ISCN, 2017). After 20 years, we are still finding new uses for the data, and we are still testing our models against these data (e.g. Sándor *et al.*, 2016).

So what does the future hold for soil organic matter research? We could be entering a new golden age because we are now working at a time when policy has caught up with the science. Since 2015 soil science has achieved new prominence. The year 2015 was the year in which the world defined and committed itself to striving toward the UN Sustainable Development Goals (UNDP, 2015), in which the historic Paris Climate Agreement was signed under the UN Framework Convention on Climate Change (UNFCCC, 2015), and it was also the UN International Year of Soils (UN, 2015).

The publication of the UN Sustainable Development Goals and the Paris Climate Agreement established an excellent legacy for the UN International Year of Soils in 2015 because they increased the recognition that soil is a critical element to the delivery of both. Several of the UN Sustainable Development Goals are underpinned by healthy soil carbon cycling, including the following Sustainable Development Goals (SDGs): SGD 1, ? no poverty in developing countries where a large proportion of their populations rely on the land for their livelihoods, and productive land relies on healthy soil (Smith *et al.*, 2013); SDG 2, zero hunger which is underpinned by the need for the soil to be able to produce safe and nutritious food (Keesstra *et al.*, 2016); SDG 13, climate action in which soil carbon sequestration offers the possibility of climate mitigation (Smith, 2016) and makes ecosystems more resilient to future climate change (Smith *et al.*, 2016a) and SDG 15, life on land which relies on healthy ecosystems that are based on healthy soil (Smith *et al.*, 2015).

Soil also plays a role in helping to deliver the Paris Climate Agreement. Under the Lima–Paris Action agenda, an international initiative was proposed to increase global soil carbon stocks by an aspirational 0.4% per year, underlining the role of soil organic matter in addressing the three-fold challenge of food and nutritional security, adaptation of food systems to climate change and mitigation of human-induced GHG emissions. Indeed, a 0.4% annual increase in global soil carbon stocks would help offset the growth of carbon dioxide in the atmosphere. This '4 per 1000' initiative (Chabbi *et al*., 2017), proposed by the French Government, was launched at COP21 in Paris and has been signed by over 30 countries and many more international partners (4p1000, 2016). Although the aspirational goal of 4 per 1000 is not without its critics (see van Groeningen *et al*., 2017; Soussana *et al*., 2017), the aim is to increase soil carbon stocks globally, with co-benefits for food security, climate change adaptation and mitigation, and several projects on these topics are underway. Smith (2016) suggested that soil carbon sequestration and biochar each have considerable potential to remove greenhouse gases from the atmosphere, in the region of 2–3 Gt CO_2-equivalents(e) year^{-1} (4–6 Gt CO_2e year^{-1} together). Carbon sink saturation means that soil carbon sequestration is time limited and that sinks are potentially revisable. Furthermore, biochar is limited by the biomass resource available as feedstock for its production. Soil carbon sequestration and biochar can remove atmospheric greenhouse gases with much less competition for land, water and nutrients than many other proposed greenhouse gas removal practices and technologies (Smith *et al.*, 2016b). Another study has suggested that the potential for greenhouse gas removal by soil organic carbon and biochar could still be greater than the above estimates (Paustian *et al.*, 2016). However, several empirical studies have reported that pyrolized carbon (char) is no more persistent than bulk SOC (Hammes et al., 2008; Singh et al., 2012, 2013; Maestrini et al., 2013), challenging the assumption underlying those large sequestration estimates. Such uncertainties point to the need for more research aimed at understanding these carbon storage potentials and how to achieve them.

Conclusion

Given the role of soil and soil organic matter in achieving the UN SDGs and the Paris Agreement, understanding soil organic matter dynamics and the accurate modelling of soil organic matter dynamics have never been more important. There is a pressing need to continue to develop our understanding of soil organic matter dynamics in the laboratory and field, and to develop, test and challenge our old and new soil organic matter models to meet the challenges that face humanity in the Twenty-first Century.

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TABLE CAPTION

Table 1 Proportion of papers featuring soil organic matter that also feature carbon in each decade since 1957.

FIGURE CAPTIONS

Figure 1 Journal papers on soil organic matter published in each decade from the Web of Knowledge search (see Methods).

Figure 2 Number of journal papers on agricultural soil carbon sequestration between 1990 and 2016

Figure 3 Disciplines of the journals in which papers on agricultural soil carbon sequestration have been published between 1990 and 2016, showing the rank by number of papers

Figure 4 Proportion of papers featuring soil organic matter that also feature: (a) fertility, (b) quality, (c) climate, (d) biodiversity, (e) health and (f) security in each decade

Figure 5 Keyword density map (www.vosviewer.com) of publications on agricultural soil carbon sequestration (a) from 1991–2002 and (b) those published in 2016.

Table 1 Proportion of papers featuring soil organic matter that also feature carbon in each decade since 1957.

Decade	1957–1966	1967–1976	1977–1986	1987–1996	1997–2006	2007–2016
Percentage of citations featuring "carbon"	8.93	3.66	3.57	30.25	41.92	51.33

Figure 1 Journal papers on soil organic matter published in each decade.

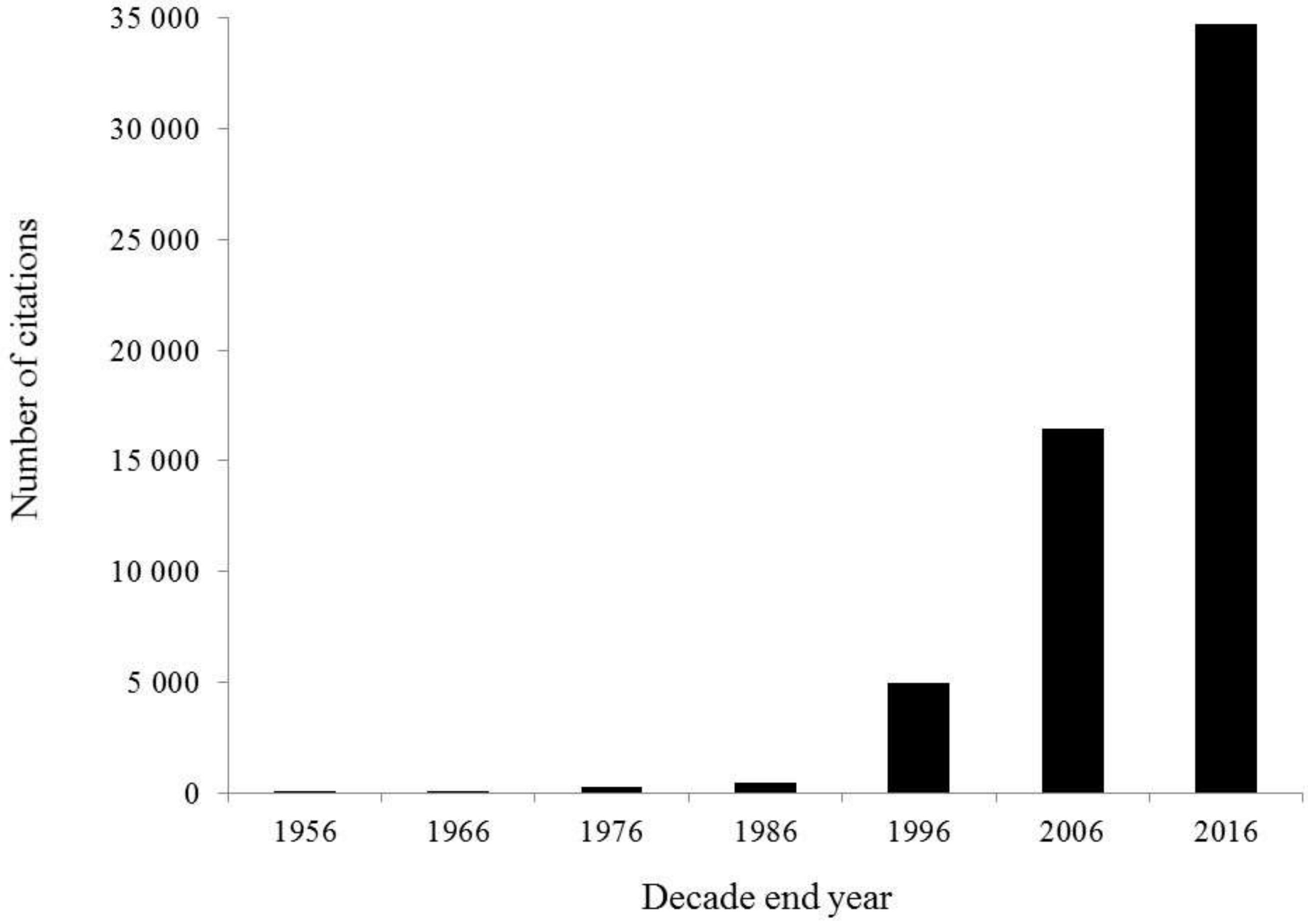

Figure 2 Number of journal papers on agricultural soil carbon sequestration between 1990 and 2016

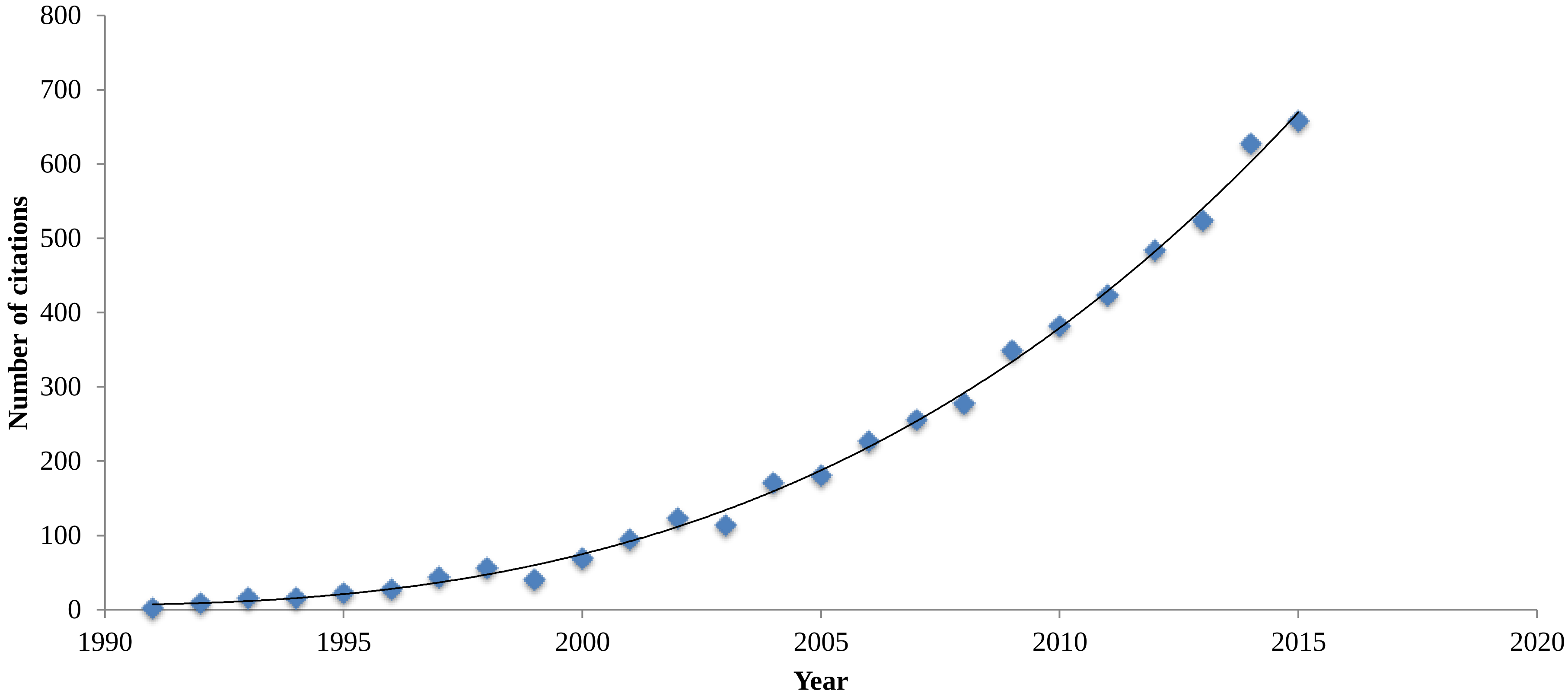

Figure 3 Disciplines of the journals in which articles on agricultural soil carbon sequestration have been published between 1990 and 2016, showing the rank by number of papers.

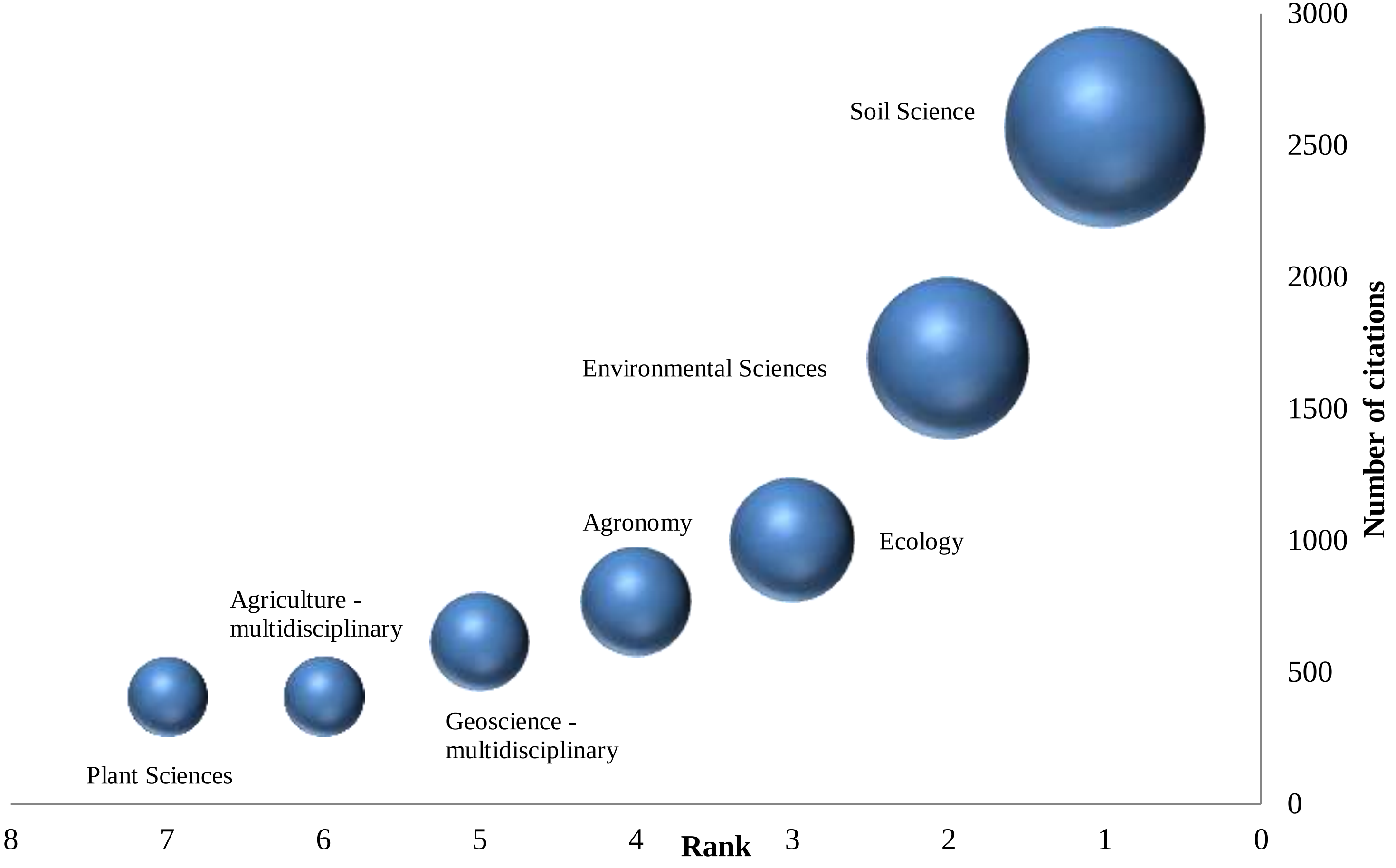

Figure 4. Proportion of papers featuring soil organic matter that also feature: (a) fertility, (b) quality, (c) climate, (d) biodiversity, (e) health and (f) security in each decade.

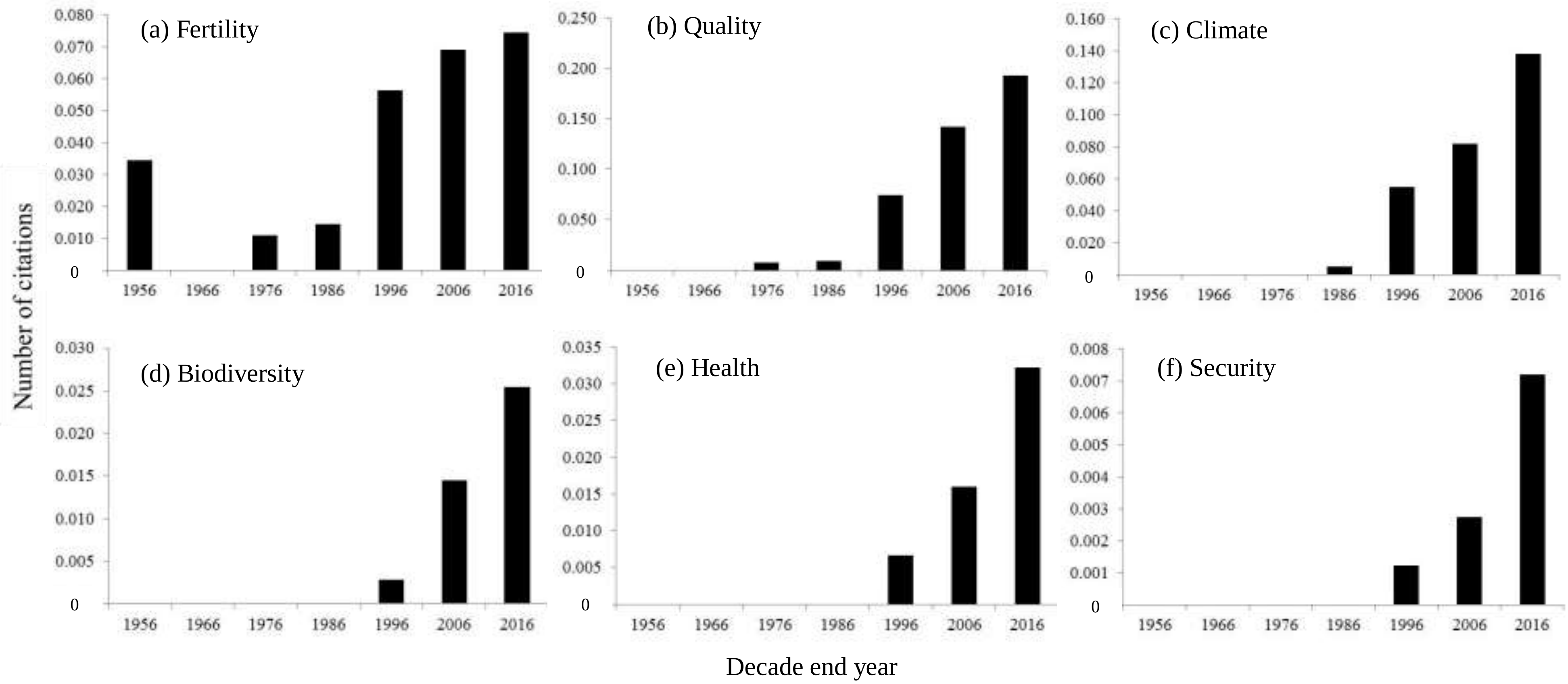

Figure 5 Keyword density map (www.vosviewer.com) of publications on agricultural soil carbon sequestration: (a) from 1991–2002 and (b) those published in 2016