Plant Soil (2020) 452:5–18
https://doi.org/10.1007/s11104-020-04550-z

REVIEW ARTICLE

How deep is the soil studied – an analysis of four soil science journals

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Received: 5 November 2019 / Accepted: 28 April 2020 / Published online: 26 May 2020

Abstract
Background and aims Soil depth is a critical attribute of any soil, and determines rooting, moisture and nutrient storage, mineral reserve, anchorage, and a range of conditions that affect plant growth. We reviewed papers from four primary soil science journals and extracted how deep the soils were studied in those papers.
Methods Soil depth was obtained over a 30-years period (1989–2019) from papers in: *European Journal of Soil Science*, *Geoderma, Plant and Soil*, and *Soil Biology and Biochemistry*. In total, 1146 papers were reviewed, and 37% (420 papers) included information on how deep the soil was studied.
Results The number of papers that included soil depth increased from 31% in 1989 to 47% in 2019. The average soil depth studied was 27 cm, but it was 53 cm between 1989 and 1999, and 24 cm between 2004 and 2019. Most of the studies were from Europe, and 41% of the papers contained soil classification. Research that focused on soil mineralogy and technology tended to study soils to a greater depth (average 74 cm), whereas the depth in soil biology research was on average 18 cm. Over 80% of the soils were sampled by fixed depth and not by soil horizon.
Conclusions Soil depth is lacking from about half of the papers in these four journals. The depth of the soil studied has halved in the past 30 years. Soil processes, soil properties, and microbial communities are depth-dependent, and for a more complete understanding, soils should be studied to a greater depth.

Keywords Soil depth · Pedon · Critical zone

Abbreviations

EC_a	Apparent electrical conductivity
EJSS	European Journal of Soil Science
EMI	Electromagnetic induction
FCC	Fertility capability soil classification system
GPR	Ground penetrating radar
SBB	Soil Biology and Biochemistry
SOC	Soil organic carbon

Introduction

Soil depth or thickness is a critical attribute of any soil. The depth determines rooting, moisture and nutrient storage, mineral reserves, anchorage, and a range of conditions that affect plant growth, or land suitability for any utilization type. Although most plant roots are found in the top one meter of soil, some plants root as deep as 8 to 18 m (Nepstad et al. 1994; Maeght et al.

Responsible Editor: Peter J. Gregory .

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2013). Deep plant roots directly and indirectly support fauna and microbial communities, and are important for soil water extraction, reducing nutrient loss, and soil carbon sequestration (Maeght et al. 2013).

Soil processes, soil properties, and microbial communities are depth-dependent (Goebes et al. 2019). Some early soil biological research quantified the changes in bacterial counts to a depth of 6 m (Houston 1893; Waksman 1916). Bacterial counts were higher in the topsoil, but bacteria were also present in the deeper subsoil. Houston (1893) found 1.7 million bacteria in 1 g of soil at the soil surface, and 410 bacteria at 1.8 m depth. Similarly, Proskauer (1892) found 45 million bacteria at a depth of 3 m, and 5 million bacteria at a depth of 6 m. In a recent study, Brewer et al. (2019) found that although bacterial and archaeal diversity decreased with depth, five understudied phyla became more abundant with soil depth. They suggested that more research is needed to quantify phyla that are more abundant deeper in the soil profile.

Currently, a considerable part of research is restricted to the top 30 cm of soil (Richter and Markewitz 1995; Harrison et al. 2010). In the early 1900s, some soil fertility studies focused on the top 50 cm of soil (Leather 1902; Bear and McClure 1920). Recent soil fertility and plant nutrition studies primarily focus on the top 30 cm of soil as for most soils the nutrients are concentrated in the A horizon (Cloud and Rupe 1994; Nishigaki et al. 2019). Few studies have focused on soils below 50 cm (Laiho et al. 1999; Wilcke and Lilienfein 2004). These studies focused on changes in plant nutrients after land use conversion (Laiho et al. 1999), and metal and nutrient storage under different land use (Wilcke and Lilienfein 2004).

Nutrient storage and availability is affected by the depth of the soil, and are important for agricultural production and plant growth (Yost and Hartemink 2019). Lilienfein et al. (2001) found that more than 40% of the total nutrient stored for cropping and pastures were in the top 30 cm of soil. About two-thirds of the nutrient for deep-rooting plants and trees is found in the top 2 m of soil, but there are large differences between soil types. McMahon et al. (2019) analyzed nutrient stocks in the top 1 m of soil in Ultisols and Oxisols under forest and cerrado. They found that 25 to 35% of N, 20% of K, 25 to 55% of P, and 25 to 60% of Ca was stored in the in the top 20 cm in soils (McMahon et al. 2019). This showed that 40% to 80% of plant nutrients are stored below 20 cm.

Soil organic carbon (SOC) studies tend to focus on 30 cm soil depth which is also the default soil depth for the carbon studies of the Intergovernmental Panel on Climate Change (IPCC 2019). This underestimates the total amount of SOC stored in the soil (Lorenz and Lal 2005; Harrison et al. 2010; Singh et al. 2018). Over half of the SOC in a pedon can be stored below 30 cm (Harrison et al. 2010; Chaopricha and Marín-Spiotta 2014). In most soils, the concentration of SOC decreases with depth, and there is potential to sequester SOC with depth. Dissolved organic matter, bioturbation, plant roots, and root exudates are the main sources of organic carbon input into deeper soil horizons (Rumpel and Kögel-Knabner 2011). As SOC inputs move deeper in the soil, the turnover rate decreases. Scharpenseel and Becker-Heidmann (1989) found in Alfisols, Mollisols, and Vertisols that the mean radiocarbon ages were 4 to 9 times higher at 100 cm soil depth than at 20 cm soil depth.

Some research has shown that subsoil SOC might be more sensitive to changes in climate, specifically temperature, than SOC in the topsoil (Fierer et al. 2003; Davidson and Janssens 2006). The potential loss of SOC in the top 3 m of soils in peatlands (Histosols) and the SOC loss of permafrost areas (Gelisols) is estimated to be 100 Pg C by the year 2100. It will reduce the SOC stocks by more than 25% of the current global estimates for those areas (Davidson and Janssens 2006). Climate change affects soil aggregate formation, chemical processes of soil organic matter adsorption and desorption onto mineral surfaces, soil water film thickness, oxygen supply for decomposition, and protection of organic matter in permafrost (Davidson and Janssens 2006). Climate change will thus affect SOC stocks in deeper soils.

There are several terms used to describe the depth of soil including effective soil depth, pedological depth, soil thickness, and solum (Plaisance and Cailleux 1981; Lozet and Mathieu 1991; Canadian Society of Soil Science 2002; Canarache et al. 2006) (Table 1). Plaisance and Cailleux (1981) defined soil depth and soil thickness as separate terms, but Canarache et al. (2006) considered soil depth and soil thickness to be the same. In this review, we use soil depth to indicate the depth to which the soil was studied.

In this review, we investigated how deep the soil has been studied in four primary soil science journals over the past 30 years. The main objective of this review was to determine the depth of soil studied (by area of

Table 1 Definitions used for soil depth, thickness, and solum

Word	Definition	Reference
Effective soil depth	The depth of soil material that plant roots can penetrate readily to obtain water and plant nutrients.	(Gregorich et al. 2002)
Soil depth	The depth of the loose layer above the solid, immobilized rock.	(Plaisance and Cailleux 1981)
Pedological depth	The depth of the weathered part above the unweathered part.	(Plaisance and Cailleux 1981)
Useful depth	The depth of the part chiefly used by plants; it always includes the A horizon, and often all, sometimes a little, of the parent rock C, when the upper part of this is fragmented or cracked.	(Plaisance and Cailleux 1981)
Soil depth/-thickness	A general term for the vertical dimension of the soil. Some authors consider it includes only the solum, some others include the solum plus the C and the G horizons (whether they represent or not the soil parent material), and some others consider it as equivalent to the root-restricting depth.	(Canarache et al. 2006)
	A more restricted sense, referring only to the vertical distance to a significant contrasting layer. It correlates with root-restricting depth, and it is used to define specific soil depth phases.	(Canarache et al. 2006)
Thickness	The thickness of the soil, in temperate climates, varies between the following limits: in the Pedological Sense: a few mm to 150 cm; in the Agronomic Sense: 10 to 35 cm; in Forestry: 10 to 200 cm. – to avoid frequent mistakes it is necessary to specify: pedological thickness, cultural thickness, etc.…	(Plaisance and Cailleux 1981)
Solum	The upper horizon of a soil in which the parent material has been modified and in which most plant roots are contained; usually consists of A and B horizons.	(Gregorich et al. 2002)
	The entire A and B horizons of the same profile and sometimes the layers exhibiting genetic features related to the development of these horizons, when they are located at the level of the C horizon.	(Lozet and Mathieu 1991)
	By convention the A and B horizons, taken together, to the exclusion of C and D.	(Plaisance and Cailleux 1981)
	A set of soil horizons, all of which are related through the same cycle of pedogenetic processes. Commonly, the solum includes the A, E, and B horizons, their transitional horizons, and some O horizons.	(Canarache et al. 2006)
	A vertical cut within the soil mantle, as can be observed in a trench or a pit. It includes all soil horizons, and also the underlying rock, of a sufficient thickness to allow its characterization. The concept is similar to that of soil profile in most other terminologies.	(Canarache et al. 2006)

research and sub-discipline). In addition, we analyzed the number of studies that included soil classification and soil properties, and determined how the soil samples were collected.

Data sources and analyses

Papers from four soil science journals were selected to analyze how deep soils were studied. We extracted data over the period 1989 to 2019 from the following journals: *European Journal of Soil Science* (*EJSS*), *Geoderma*, *Plant and Soil*, and *Soil Biology and Biochemistry* (*SBB*). These are primary journals that are broad and generic (*Geoderma, EJSS*), have an edaphological focus (*Plant and Soil*), and they all have high impact. Within this 30-year period, we focused on 7 years: 1989, 1994, 1999, 2004, 2009, 2014, and 2019. Of each journal and year, the first 15 papers that included soil depth were used in this review, and a total of 420 papers were analyzed. Review papers, short communications, and research papers that had no information on soil depth were excluded from this study. In total, 1146 papers were examined, and 37% of those included information on the soil depth (Table 2). About 41% percent of the papers analyzed from *Soil Biology and Biochemistry* and *European Journal of Soil Science* included soil depth (Fig. 1), whereas soil depth was given in 31% of the papers from *Geoderma* and *Plant and Soil.*

From each paper, soil depth, sample collection method (fixed depth or by horizon), soil properties, and total number of samples was extracted. Other data that was extracted included geography (site location, location of authors) and soil classification. All papers were classified based on the focus of research and a soil science sub-discipline. The studied soils were classified according to *Soil Taxonomy* (Soil Survey Staff 2014), and if the soil was classified using another system, it was converted to *Soil Taxonomy*.

Results

Soil depth

The number of papers that include soil depth increased over time. In 1994, 28% of papers included soil depth, whereas by 2009 it was 52%. The average soil depth that was studied in the 420 papers was 27 cm (Fig. 2). Papers from the *European Journal of Soil Science* studied soils deeper than in the other three journals. The soil depth studied in *Plant and Soil* and *Geoderma* were 26 cm, and papers in *Soil Biology and Biochemistry* had an average soil depth of 18 cm. The depth of soil that was studied in the 420 papers of these four journals decreased over time. Between 1989 and 1999, the average soil depth studied was 53 cm, whereas the average between 2004 and 2019 was 24 cm. There is considerable variation in the depth of the soil studied. For example, Öborn (Öborn 1989) studied acid sulfate soils in Sweden and collected soil samples up to 3 m depth, and Nahon et al. (1989) studied soils in Brazil to 20 m depth. Several papers studied soils below 2 m depth (i.e. Marcelino et al. 1999; Siemens et al. 2004). Studies that focus on modeling (i.e. mapping, vis-NIR predictions), such as Dobermann (1994) and Lark and Ferguson (2004), collected thousands of samples but from only 20 cm soil depth.

About 42% of the 420 papers are from authors and research that was conducted in Europe, and in total 38% of the papers had authors and study sites in Asia or North America (Fig. 3). Few papers were from Africa and Central and South America (9% of the papers).

Soil orders and focus

Of the 420 papers that included soil depth, 41% had classified the soils (Fig. 4). Of those soils classified, 41% of the soils were classified as Inceptisols or Alfisols, 34% were Entisols, Ultisols, or Mollisols, and less than 6% of the soils were classified as Andisols, Aridisols, Gelisols, or Histosols. About half of the papers on Inceptisols and Entisols were from Europe. Most Spodosols were studied in Europe, and a small portion were from North America, Africa, and Central and South America. Most of the Andisols papers were from Asia, and all of the Gelisols studied were in North America.

On average, Aridisols were studied the deepest (125 cm), however, few samples have been collected (Fig. 5). Entisols and Vertisols had an average depth of 88 and 72 cm, respectively. The average depth studied for Gelisols, Oxisols, Alfisols, and Andisols was between 40 to 50 cm. Spodosols and Inceptisols were the shallowest, having an average depth of 19 and 27 cm, respectively. The maximum depth studied in Ultisols was 1200 cm and 1130 cm in Mollisols. The shallowest depth studied in most soil orders was less than or equal to 10 cm with the exception of Aridisols and Gelisols (30 cm minimum).

The focus of research was broadly classified into four groups: environmental, agricultural, forestry, and ecology. The main research focus for over 50% of the papers was on an environmental aspect (Fig. 6). *Geoderma* had slightly more papers focused on the environment than the other journals. Approximately 27% of papers focused on agriculture, 13% on forestry, and 4% on ecology. Sixty-four percent of the papers that focused on agriculture were published in the *European Journal of Soil Science* or *Plant and Soil*. Approximately 38% of papers that focused on forestry were published in *Plant and Soil*, and 59% of papers that focused on ecology were published in *Soil Biology and Biochemistry*.

Soil depth was studied differently for each focus area. Soils under agriculture were studied on average up to 30 cm soil depth and were similar to soils under forest (28 cm) (Fig. 7). Research that focused on ecology studied soils up to 21 cm depth.

The papers were grouped into six soil sub-disciplines: soil biology, soil chemistry, soil physics, soil fertility and plant nutrition, pedology, and other (soil technology, soils and environment, mineralogy). Over 50% of papers were on soil biology (24%), soil chemistry (20%), or soil fertility and plant nutrition (17%) (Fig. 8). Only 5% of papers were on soil technology and mineralogy (data not shown).

In *Plant and Soil*, 42% were on soil fertility and plant nutrition, 19% on soil physics and soil chemistry, and less than 2% were on pedology and mineralogy. There were no papers in *Plant and Soil* on soil technology. In *Geoderma*, about 69% of papers were on soil chemistry

Table 2 Meta-data of the four journals from which 1146 papers were reviewed and analyzed for the years 1989, 1994, 1999, 2004, 2009, 2014 and 2019

Journal	Year	Volume(s)	Number of papers		Papers with depth information (%)
			Reviewed	Included soil depth	
European Journal of Soil Science	1989	40	53	15	28
	1994	45	49	15	31
	1999	50	24	15	63
	2004	55	34	15	44
	2009	60	27	15	56
	2014	65	28	15	54
	2019	70	31	15	48
	Total		246	105	43
Geoderma	1989	44–45	35	15	43
	1994	61–63	52	15	29
	1999	88–90	50	15	30
	2004	118–119	31	15	48
	2009	149	29	15	52
	2014	213–216	92	15	16
	2019	333–334	38	15	39
	Total		327	105	32
Plant and Soil	1989	113–114	50	15	30
	1994	158–160	66	15	23
	1999	206–208	53	15	28
	2004	258–259	57	15	26
	2009	314–315	40	15	38
	2014	374	27	15	56
	2019	434–435	38	15	39
	Total		331	105	32
Soil Biology and Biochemistry	1989	21	56	15	27
	1994	26	47	15	32
	1999	31	40	15	38
	2004	36	27	15	56
	2009	41	20	15	75
	2014	68	30	15	50
	2019	128–129	22	15	68
	Total		242	105	43
Total			1146	420	37

(28%), pedology (23%), or soil physics (18%) (Fig. 8). Few papers (<13%) focused on soil fertility and plant nutrition, soil technology, or soil biology. Fifty-six percent of papers in the *European Journal of Soil Science* were on soil chemistry (32%) or soil physics (24%). Less than 25% of papers in *European Journal of Soil Science* were on soil fertility and plant nutrition, pedology, mineralogy, and soil technology. About 60% of papers in *Soil Biology and Biochemistry* were on soil biology, 14% in soils and the environment, 12% in soil fertility and plant nutrition, 10% in soil chemistry, and 5% in soil physics. There were no papers in *Soil Biology and Biochemistry* on pedology, mineralogy, or soil technology.

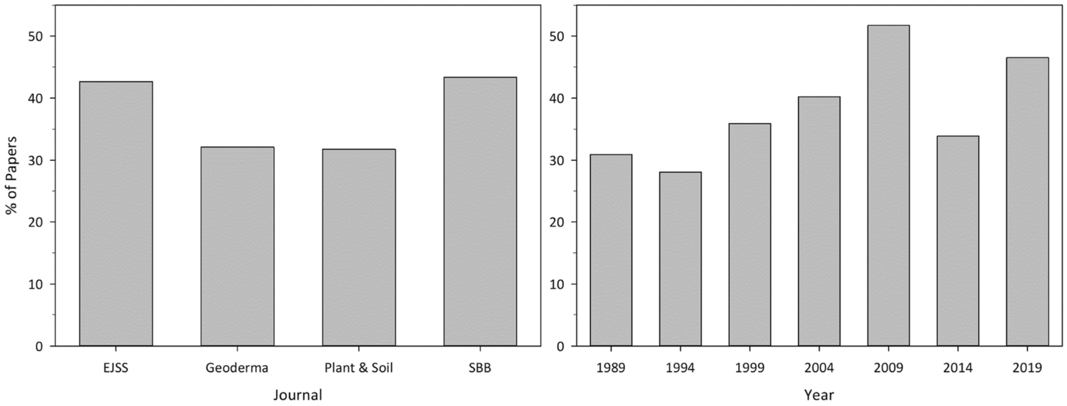


Fig. 1 Percentage of papers that included information how deep the soil was studied, by journal and at five-year increments between 1989 and 2019. EJSS = European Journal of Soil Science, SBB = Soil Biology and Biochemistry

The depth of the soil was studied differently for each sub-discipline. Research that focused on mineralogy and soil technology tended to study soils up to 175 cm and 61 cm depth, respectively (data not shown). The depth of the soil studied in soil physics, chemistry, pedology, and soil fertility and plant nutrition was between 25 and 28 cm (Fig. 7). Most soil biology research studied soils up to 18 cm depth.

Sample collection

The sample collection method (fixed depth or by horizon) was extracted from each paper and 81% of papers collected soil samples by fixed depth (Fig. 9). More than 90% of the papers in *Soil Biology and Biochemistry* and *Plant and Soil* sampled the soils by fixed depth and not by soil horizon. Approximately 35% of the papers in *Geoderma* and 24% of the papers in *European Journal of Soil Science* presented soil data that was collected by horizon. The number of papers that sampled the soil by horizon decreased over time, from 41% of the papers in 1989 to only 5% of the papers in 2014 and 2019.

Soil properties

The depth of the soil was studied differently for each soil property (Fig. 10). Soils used for mineralogy and weathering studies were studied the deepest, having an average depth of 127 cm (range: 5–2000 cm). Studies that used infrared spectroscopy analyzed soils between 5 and 150 cm (average: 31 cm). The average depth for soils analyzed for soil carbon was 23 cm, but ranged from 2 to 560 cm. Microbial studies had the lowest average soil depth, and bacteria was studied to approximately 22 cm, 21 cm for microbial biomass, and 15 cm for fungi.

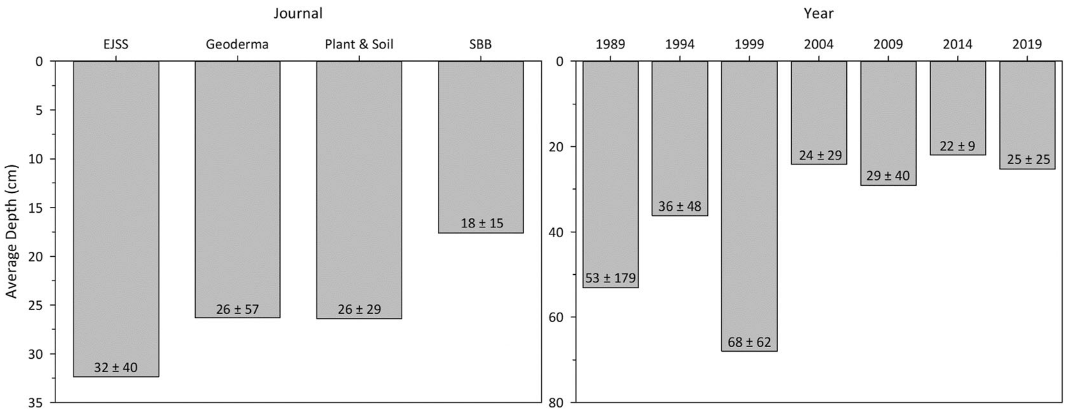


Fig. 2 Average soil depth studied in 420 papers by journal and for five-year increments between 1989 and 2019 (mean cm ± SD). EJSS = European Journal of Soil Science, SBB = Soil Biology and Biochemistry

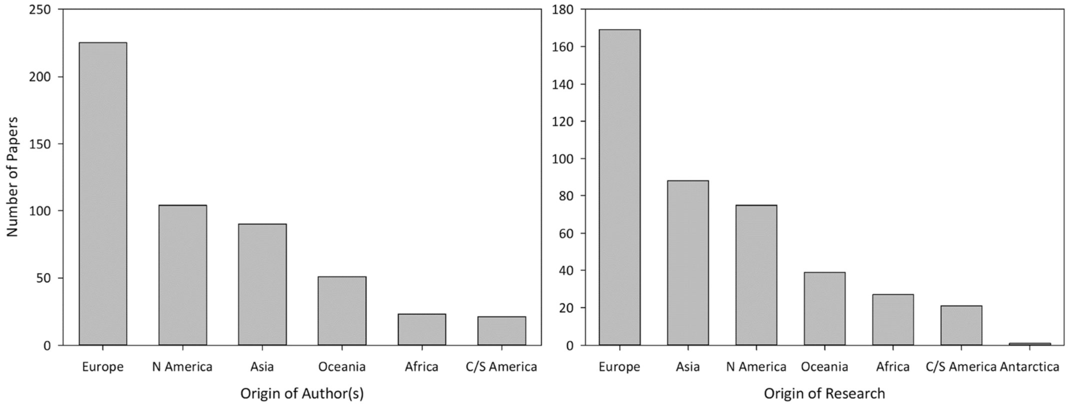


Fig. 3 Origin of author(s) and origin of research of 420 papers that included the depth of the soil(s) studied

Discussion

Approximately 63% of papers in *European Journal of Soil Science*, *Geoderma*, *Plant and Soil*, and *Soil Biology and Biochemistry* did not include soil depth. However, the number of papers that included soil depth increased over time, but the percentage is low (31% in 1989 and 47% in 2019). The average soil depth studied in these four journals was approximately 53 cm between 1989 and 1999, but only 24 cm between 2004 and 2019. The number of papers that include soil depth is increasing, but the depth of the soil being studied is becoming

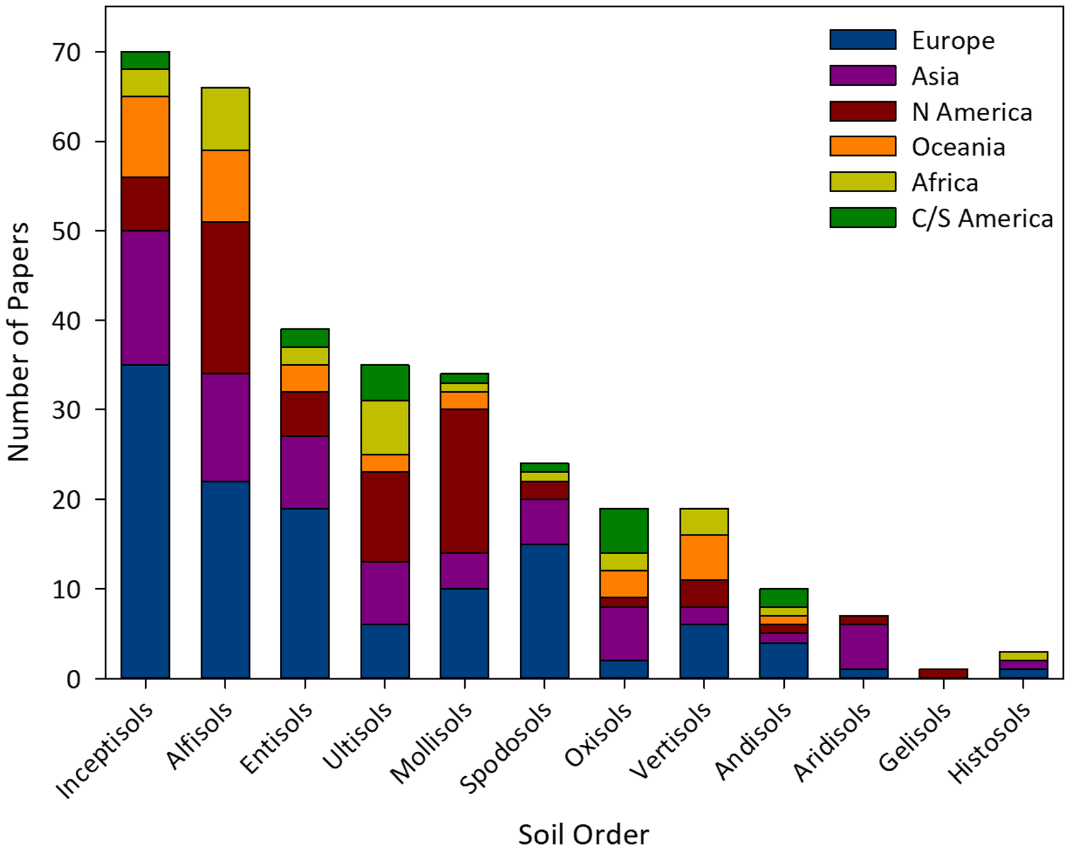


Fig. 4 Soil orders of the 420 papers in four soil science journals that included the depth of the soil(s) and the geographic spread. Soil classification was not given in 41% of the papers that had included soil depth

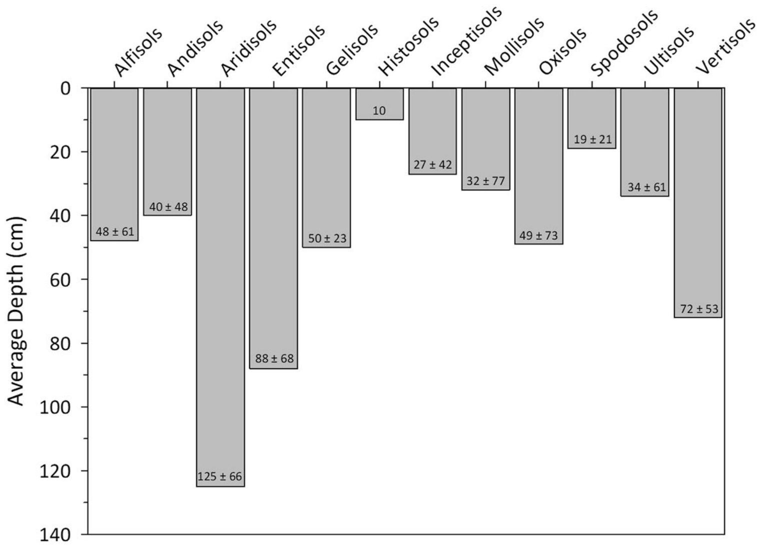


Fig. 5 Average soil depth studied in 420 papers by soil order (mean cm ± SD)

shallower. We have no explanation for this trend but the focus on shallower sampling depths may reflect a decreased attention towards whole pedon studies. This may be due to an increase in studies focusing on soil attribute mapping and modeling.

The average number of papers that have soil depth in the title was around six per year in the 1990s and is currently around 30 per year (Scopus data). Only one paper from this review had soil depth in the title. Papers with soil depth in the title in the 1990s focused on soil degradation (Kruger et al. 1993), nitrate (Willems et al. 1997), nutrients (Pieters and Baruch 1997), and leaching (Johnson and Lavy 1994). Fewer papers focus on soil thickness, and most of these have focused on probability mapping across using models and digital soil mapping techniques (Bonfatti et al. 2018; Chen et al. 2019).

From this review, 27% of the papers focused on agriculture, 13% on forestry, and 4% on ecology. Over 270 papers were published with soil depth in the title in the 2010s, and 65% of the papers focused on agricultural and biological sciences (Scopus data). The highest cited papers recently published focused on plant trait convergence and divergence along a soil depth gradient (Bernard-Verdier et al. 2012), extracellular enzyme activity and microbial community structure with soil depth (Stone et al. 2014), and microbial biomass C, N, and P,

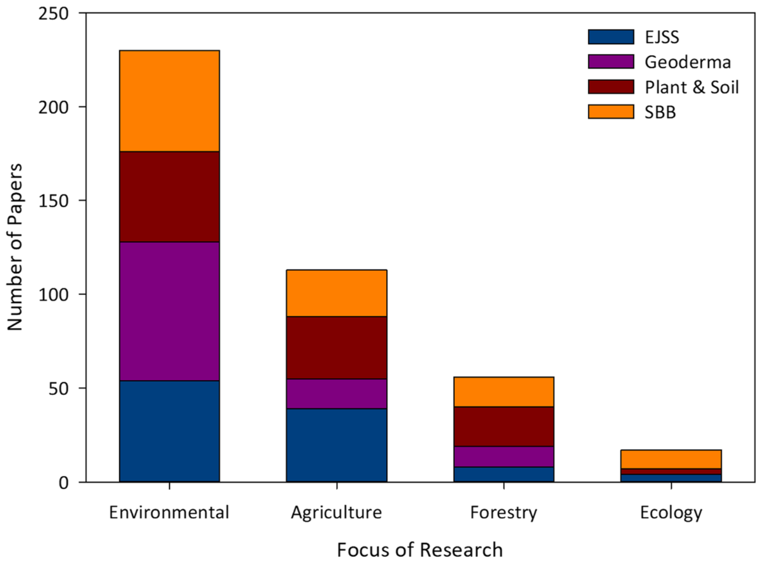


Fig. 6 Focus of research of the 420 papers that included the depth of the soil(s) studied. EJSS = European Journal of Soil Science, SBB = Soil Biology and Biochemistry

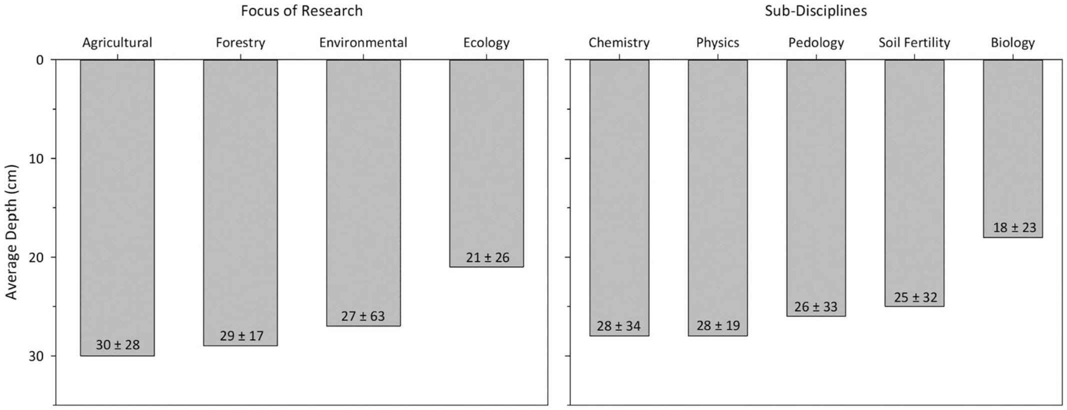


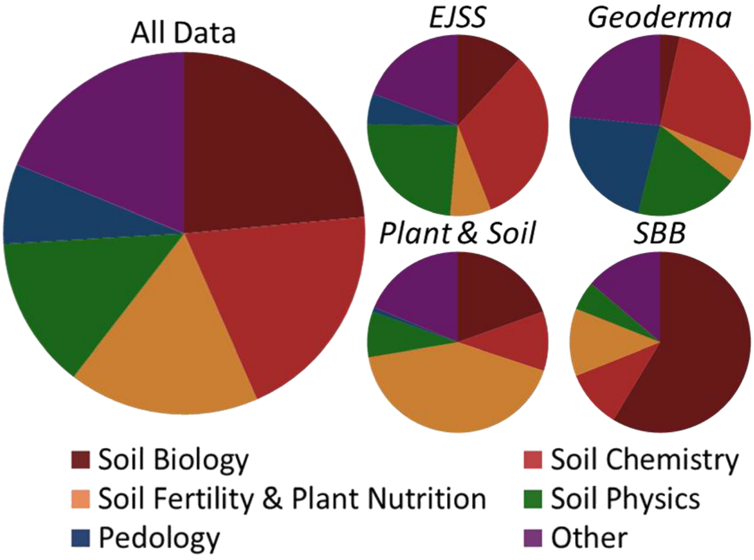
Fig. 7 Average soil depth studied in 420 papers by focus of research and soil science sub-discipline (mean cm ± SD)

microbial communities, and microbial carbon use efficiency by soil depth (Aponte et al. 2010; Steven et al. 2013; Spohn et al. 2016). Other studies focused on SOC, water repellency, aggregation, and root biomass (Hassouna et al. 2010; De Graaff et al. 2014). Most of the recent soil biology papers only study soil to a maximum of 30 cm soil depth (Nombela et al. 1999; Li et al. 2019). Soil ecology papers studied soils up to 21 cm depth.

Although much of soils research focuses on the top 30 cm of soil, numerous studies and reports have suggested how deep soils should be studied. In the 1990s, the average soil depth studied was 53 cm, whereas it was approximately 24 cm in the 2000s. In the late 1800s, Whitney (1900) stated suggested sampling to a depth of 3 ft (90 cm) in the eastern and 6 ft (180 cm) in the western part of the USA. According to *Soil Taxonomy*, the lower limit of the soil for classification purposes is 2 m (Soil Survey Staff 2014), but much of the information provided in soil surveys is on A and B horizons (Wysocki et al. 2005). The C horizon may be considerably thicker than A and B horizons. Often there is more variation in C horizon soil properties since it is affected by the geology and parent material (Winters and Simonson 1951). Over 80% of the papers reviewed used fixed depth to collect the soil samples, and less than 10% of the studies sampled by soil horizon.

Soil depth is important information when classifying the soil. Of the 41% of papers that contained soil classification, 41% were classified as Inceptisols or Alfisols, 34% were Entisols, Ultisols, or Mollisols, and less than 6% were classified as Andisols, Aridisols, Gelisols, or

Fig. 8 Soil sub-disciplines of the 420 papers that included the depth of the soil(s) studied. EJSS = European Journal of Soil Science, SBB = Soil Biology and Biochemistry



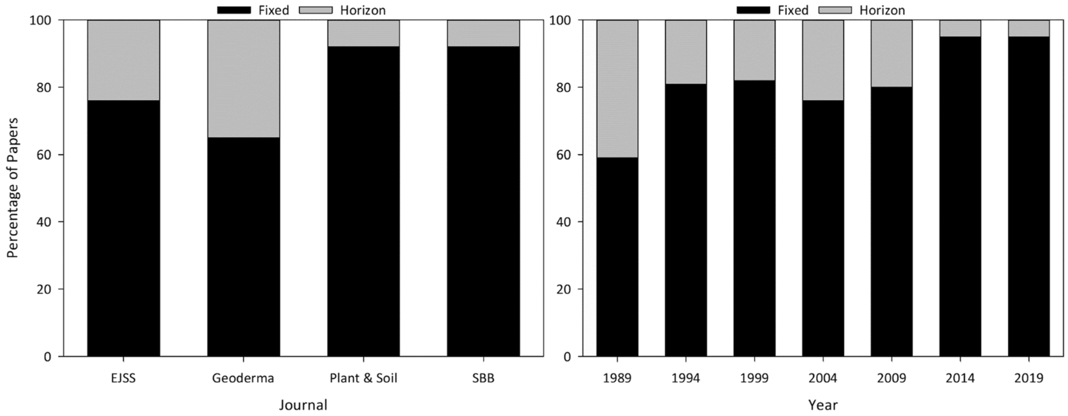
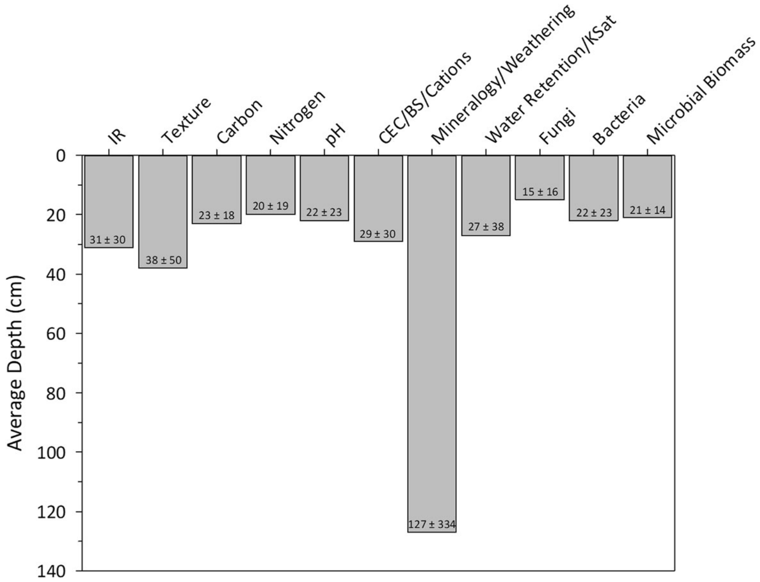


Fig. 9 Sample collection (by horizon or fixed depth) of 420 papers that included the depth of the soil(s) by journal and for five-year increments between 1989 and 2019. EJSS = European Journal of Soil Science, SBB = Soil Biology and Biochemistry

Histosols. *Soil Taxonomy* has soil depth classes for mineral soils and Histosols. All families of mineral soils and Histosols that have a root-restricting layer at a specific depth below the mineral soil surface, use soil depth classes with the exception of families with a fragipan or Lithic subgroups. Root-restricting layers included in the soil depth classes are: (a) duripans, petrogypsic, petrocalcic, and placic horizons, (b) continuous ortstein (> 90%), and (c) densic, lithic, paralithic, and petroferric contacts. For mineral soils and Histels, Oxisols that are less than 100 cm deep that are not in a Lithic subgroup and are root-restricting are considered shallow. Similarly, other mineral soils and Folistels that are not in a Lithic subgroup, are root-restricting, and are less than 50 cm deep are classified as shallow. Other Histels that are less than 50 cm deep to a root-limiting layer are considered to be shallow. No soil depth class is used for all other Histosols and mineral soils (Soil Survey Staff 2014).

For tropical regions, the Fertility Capability Soil Classification (FCC) system uses soil depth as a condition modifier. According to the FCC system, soils that have a rock or a root-restricting layer within 50 cm soil depth are considered shallow. Plants are not able to root as deep in shallow soils, limiting the available water and nutrients typically found in deeper soils. By this definition, shallow soils cover approximately 2% of tropical lands worldwide (98 million hectares) (Sanchez et al. 2003).

Fig. 10 Average soil depth studied in 420 papers by soil property. Error bars represent the standard deviation from the mean



Studying soils with depth requires digging a soil pit or taking a soil core by horizon or at fixed depths. Due to the advancement in technology, non-invasive techniques (proximal and remote sensors) are being used more frequently since it allows researchers to study deep soils without collecting soil samples. Two proximal soil sensors that are commonly used are electromagnetic induction (EMI) and ground penetrating radar (GPR). Both methods collect data quickly over a large extent (Doolittle and Collins 1998), and are used for spatial and temporal analyses (Serrano et al. 2014). Electromagnetic induction measures the apparent electrical conductivity (EC_a) of the soil which can be related to soil moisture and soil texture (sand, silt, clay content) (Yost et al. 2019) as well as salinity, temperature, and soil mineralogy (Castrignanò et al. 2012). Several EMI instruments have been used, such as EM31, EM38, DUALEM 1S, and Veris 200 XA, and the effective depth of exploration is different for each instrument. The effective depth of exploration for the EM31 instrument is approximately 6 m, 1.5 m for the EM38 and DUALEM 1S, and 0.3 m for the Veris 200 XA (Doolittle and Collins 1998; Castrignanò et al. 2012).

Ground penetrating radars have been used to estimate soil water table depths, soil water content, and groundwater flow patterns (Doolittle et al. 2006; Weihermüller et al. 2007). They have also been used to survey root biomass in forest systems (Butnor et al. 2003), to detect biogenic gas accumulations in peat soils (Comas et al. 2005), and estimate depths to soil horizons, hard pans, dense till, and permafrost (Doolittle and Collins 1995). Ground penetrating radars collect soil information using antenna frequencies. If a GPR has a high frequency, it will provide higher resolution information for shallower soil depth, and if a GPR uses a low frequency, it will be able to get more information about the soils at deeper depths (Doolittle and Collins 1995).

Remote sensing has also been used to study soil properties in a non-invasive way. The number of publications on remote sensing has increased significantly since the mid-2010s (Weiss et al. 2020). Sensors (e.g. visible near infrared spectrometer, gamma-radiometer, very high-resolution radiometers) are commonly mounted on airplanes and satellites, and are able to collect land and soil information such as vegetation, soil moisture, soil texture, and digital elevation models using radiance energy, gamma radiation, surface reflectance, surface temperature, and visible spectral imageries (albedo) (McBratney et al. 2000). Unlike GPR and EMI, remote sensors are only able penetrate through the top 5 cm of soil or less. For example, the Station Soil Moisture Monitoring Networks and NASA-SMAP (L3_SM_P) datasets only measure and estimate soil moisture in the top 5 cm (Huang et al. 2020).

Conclusions

This review investigated how deep the soil has been studied over the past 30 years in four primary soil science journals. Approximately 63% of papers reviewed from *European Journal of Soil Science*, *Geoderma*, *Plant and Soil*, and *Soil Biology and Biochemistry* did not include soil depth. The number of papers that included soil depth increased from 28% in 1994 to 52% in 2009. The average soil depth studied from the 420 papers was 27 cm, and has decreased over time. Approximately 41% of the papers had classified the soils, and approximately 41% of the soils were Inceptisols or Alfisols. The main research focus was on an environmental aspect, and 27% of the papers focused on agriculture. Research that focused on mineralogy and soil technology tended to study deep soils (61–175 cm), and soil depth in soil biology research was generally less than 20 cm. Information on soil depth is lacking from many papers, and the depth of soil being studied has decreased (~53 cm in 1990s, ~24 cm in 2000s). There has been rapid advancement in non-invasive analytical techniques, and soil in recent decades are studied more shallow. Many soil processes, soil properties, and microbial communities are depth-dependent, and soils need to be studied more deeply if we were to increase our understanding of its relationship to the wider environment.

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