The potential impacts of soil sampling on erosion

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The potential impacts of soil sampling on erosion

Abstract

It is well known that soil is subject to many natural and human-induced threats, which contribute to its degradation and loss. In addition, sampling for scientific studies and professional activities increase soil loss, because the samples - often in excessive amount - are never restored to the original place. Here, we propose to call “hidden erosion” this unwelcome form of erosion. A rough estimation of the "hidden erosion" has not been carried out before. In this paper, the amounts of soil sampled from its original site and transferred to the laboratory is estimated using data of selected literature studies; the equivalent soil thickness reduction is calculated. From these estimates, we demonstrate that, in most cases, the amounts of soil sampled exceed the tolerable loss. This erosion form cannot usually heavily impact the environment, because of its limited spatial and temporal extent. However, when the soil is removed repeatedly on a large spatial scale, sampling may increase the erosion rates of the natural and other human-induced processes at the global scale.
Finally, since sampling cannot usually be avoided in soil studies, a decalogue with some careful measures to minimize the soil loss during sampling is proposed, in order to limit the "hidden erosion".

Keywords Hidden erosion; soil thickness reduction; tolerable soil loss; soil degradation; soil sampling decalogue.

Introduction

The soil plays several functions for the living beings, since it supports plant growth, produces food and energy, benefits human societies in several areas, including water filtering, waste decomposition, carbon storage, mitigation of greenhouse gas emissions and global warming, and hosts a great diversity of fauna and microbial communities. At the same time, soil is a finite and slowly renewable resource, since it is subject to several factors of quality reduction, leading to unsustainable decay rates (Panagos et al. 2015). Among these threats, soil erosion is one of the most severe and alarming degradation factors, since it dramatically reduces the role of key resource played by soil for human well-being (FAO 2015). It should be noted that it is impossible to stop soil erosion, which is a natural geological process. Nevertheless, the unique goal at the planetary scale is to manage the human impacts on the soil so that the erosion rates are within an acceptable range (FAO 2019), avoiding that the rate of soil loss exceeds that of soil formation (Alewell et al. 2015). Based on the Web of Science database (accessed on November 2019), the literature published on soil erosion in the 2016-2018 period (7348 articles in two years only) even exceeded the production of the whole 20th Century (5698 articles between over sixty years between 1931 and 1999). Despite such continuous research over time, soil erosion by water, wind and tillage is still among the major threats to this resource in almost all the regions of the World (FAO 2019). In addition to the well-known and documented reasons of soil erosion (weathering, excessive grazing, tillage and unsuitable agricultural practices, deforestation, fire, and landslides) (e.g., Borselli et al. 2006; Sharifi et al. 2017; Lal 2019), soil sampling is a human-induced factor that may contribute to erosion. The effects of soil erosion on the total loss at the global scale has been practically neglected as far as now. Sampling cannot be avoided in soil science, since it is essential in many research activities, such as the characterization of physical, chemical and microbiological properties of soils, and the simulation of many natural and anthropogenic processes of soil. For more than a century, soil samples have been collected by scientists and transported to laboratories for the analyses. Therefore, huge amounts of soil have been taken away from their original location and thrown away, and thus not returned to the original place. In order to indicate this less known form of soil erosion, we take the liberty to use the terms "hidden erosion". As far as now, no studies have quantified the amounts of soil subject to the "hidden erosion" and compared these amounts to the natural and/or anthropogenic erosion rates. To fill this gap, this study evaluates the soil loss due to sampling based on a dataset of 40 papers randomly selected in the bibliography (2010 to 2019); an estimation of the soil thickness reduction due to the "hidden erosion" and a comparison with the tolerable soil loss worldwide have been carried out.

Materials and methods

In order to find the published studies in which samples were collected for investigations on soil erosion, a bibliographic research has been carried out in November 2019 , based on the following keywords: soil sampling design and collection method, kg soil collected, soil sample collection and preparation, soil sampling design of the study area, soil sampling procedure, soil sampling methodology and soil sampling scheme. Approximately 600 studies have been identified worldwide, and 40 papers from 2010 to 2019 have been randomly selected and analyzed (Figure 1). The unpublished studies have not been considered.

The following parameters have been extracted and analyzed:

- Number of collected samples (hereinafter "N")
- Sample weight ("SW")
- Net soil loss ("NSL"), equal to the product N·SW
- Soilthickness reduction due to sample collection ("STR").

STR was calculated from NSL, using a value of the bulk density of 1200 kg m^{-3} (Montgomery 2007).

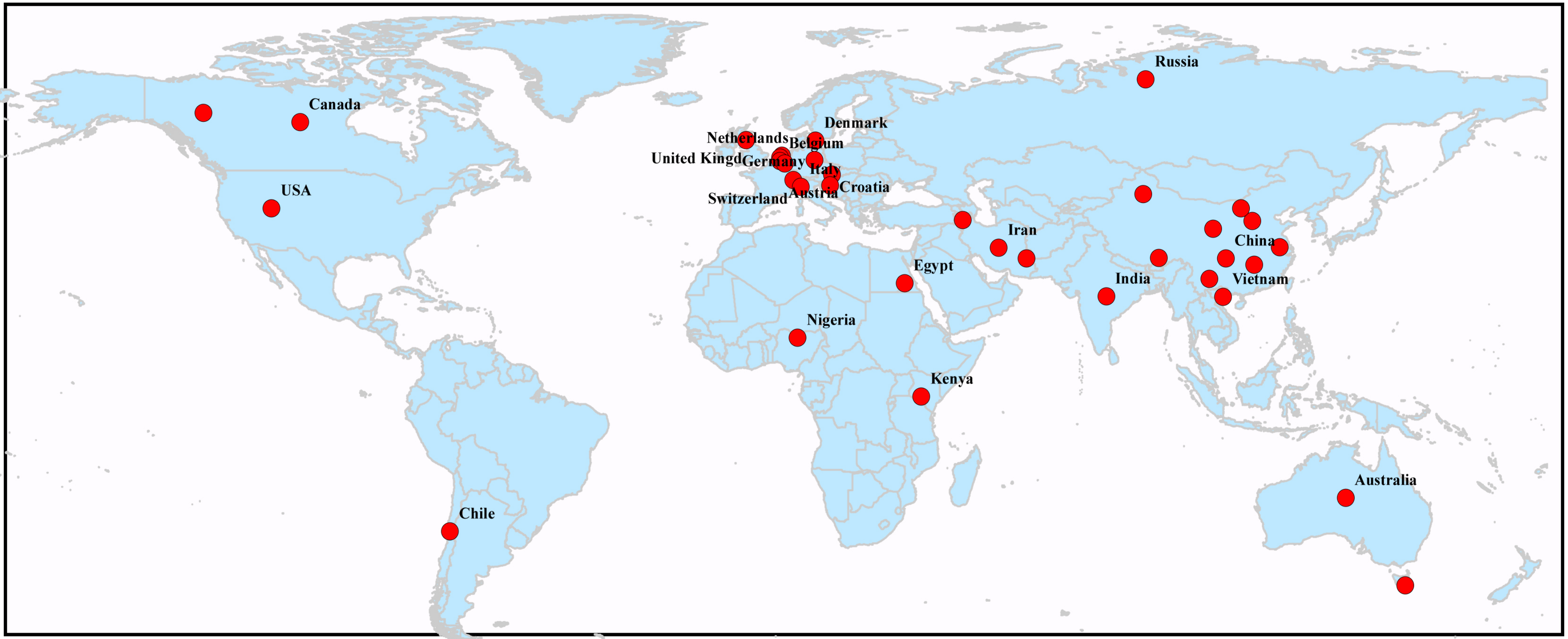

Fig. 1 Map of the sites analyzed by the 40 papers selected in this study.

Results

Table 1 reports the amount of soil collected from the natural site and the equivalent soil thickness reduction in the selected papers, while an estimation of the soil disturbance due to sampling is reported in Figure 2. The number of soil samples ranges from one (Pelster et al. 2018) to 1060 (Shi et al. 2019) with an average value of 138 samples. Each sample weighs on the average 100 kg with a maximum value of over 1000 kg (Ruttens et al. 2010 and Van de Voorde et al. 2011) (Table 1). Based on these data, the transferred soil - quantified by the NSL parameter - ranges from 12 kg (Girsowicz et al. 2018) to even 1832 kg (Shi et al. 2019) with a mean of about 397 kg of soil per study. Therefore, STR in the selected studies is between 0.001 and 0.153 mm ha^{-1} (on the average 0.033 mm ha^{-1}).

If the tolerable soil losses (TSL) are assumed from erosion studies worldwide (FAO 2019), out of 40 selected studies of Table 1, 19 (47.5% of the total) show a STR of 1.4 mm, higher than a TSL between 0.02 and 0.11 mm yr^{-1} for Europe (Verheijen et al. 2009), while in 22 studies (55.0%) STR is higher than a TSL of 0.015 mm yr^{-1} for Australia (Bui et al. 2011).

Overall, if the mean weight of the removed soil (397 kg soil per study) is multiplied by the total number of the papers annually published (42000) about soil science (Hartemink 2019), a total soil loss of 16682 tons per year due to the "hidden erosion" can be estimated. This value is even more surprising, if we consider that this soil loss only account for the published studies, but it excludes the unpublished researches. Considering both published and unpublished papers, the amount of lost soil surely far exceeds the above-mentioned values.

It should be noted that Aksoy et al. (2016), in their study covering all Europe, removed 20000 soil samples weighing 10 tons, but we did not consider it in this study, to avoid bias in our results.

Discussions and conclusions

Soil analysis unavoidably relies on sampling, which requires removal of soil volumes from their natural places. The results of this study have demonstrated that the "hidden erosion" is an unusual but impacting form of soil erosion, which should be considered in addition to the natural and human-induced geological processes at the global scale.

While it is obvious that, when the studied soil is polluted with hazardous substances or biological agents (e.g., heavy metals, pathogens), it is permanently removed, it is less understandable that, in the other cases (e.g. sampling of uncontaminated agricultural or forest soils), the collected samples are not returned to their original location.

Table 1 Characteristics of soil sampled from the original site and its equivalent thickness reduction in a selection of papers about soil science.

ID	N	SW (kg per sample)	NSL (kg per study)	STR (mm ha^{-1} per study)	Reference
1	15	5	75	0.006	(Paz-Ferreiro et al. 2012)
2	30	20	600	0.050	(Khan et al. 2014)
3	916	2	1832	0.153	(Sollitto et al. 2010)
4	154	5	770	0.064	(Jansa et al. 2014)
5	10	25	250	0.021	(Pourbabaee et al. 2018)
6	1060	0.97	1028	0.086	(Shi et al. 2019)
7	72	0.5	36	0.003	(Guan et al. 2018)
8	160	2	320	0.027	(Shahriari et al. 2019)
9	66	2	132	0.011	(Shaddad et al. 2019)
10	300	1	300	0.025	(Lv 2019)
11	1	400	400	0.033	(Farrell et al. 2010)
12	90	1	90	0.007	(Zhao et al. 2019)
13	232	4	928	0.077	(Nyiraneza et al. 2017)
14	12	2.5	30	0.002	(Zhang et al. 2015)
15	50	1	50	0.004	(Buzmakov et al. 2019)
16	160	1	160	0.013	(Capra et al. 2018)
17	166	1	166	0.014	(Zhang et al. 2016)
18	1	1000	1000	0.083	(Ruttens et al. 2010)
19	400	0.5	200	0.016	(Behera and Shukla 2015)
20	537	0.94	506	0.042	(Fu et al. 2016)
21	60	2	120	0.01	(Usikalu et al. 2014)
22	1	30	30	0.002	(Pelster et al. 2018)
23	1	200	200	0.017	(Houben et al. 2012)
24	27	50	1350	0.112	(Verdejo et al. 2016)
25	1	560	560	0.047	(Bruun et al. 2015)
26	6	2	12	0.001	(Verchot et al. 2011)
27	1	1000	1000	0.083	(Van de Voorde et al. 2011)
28	2	70	140	0.012	(Goberna et al. 2011)
29	105	1	105	0.009	(Jiang et al. 2017)
30	150	2	300	0.025	(Ebrahimi et al. 2019)
31	3	233	699	0.058	(Sagarkar et al. 2014)

32	8	50	400	0.033	(Shaheen et al. 2015)
33	469	1.5	703.5	0.059	(Zhang et al. 2012)
34	5	10	50	0.004	(Banerjee et al. 2016)
35	48	1	48	0.004	(Laird et al. 2010)
36	1	200	200	0.017	(Farrell and Jones 2010)
37	4	50	200	0.017	(Kirkby et al. 2013)
38	40	0.5	20	0.002	(Le et al. 2019)
39	127	1	127	0.011	(Wang et al. 2013)
40	12	62.5	750	0.062	(Van de Voorde et al. 2012)
Min.	1.0	0.5	12	0.001	-
Mean	137.6	100.0	397.2	0.033	-
Max.	1060.0	1000.0	1832.0	0.153	-

Notes: N = number of collected samples; SW = sample weight; NSL = net soil loss; STR = soil thickness reduction.

Fig. 2 Some of the soil disturbance examples due to sampling in soil research studies. (Sources: ttps://www.tarleton.edu (photo 1), https://coas.siu.edu (photo 3),http://landjudging.org (photo 5), https://www.hoosiertimes.com (photo 6), https://sustainablesoils.org (photo 8); the photos 2, 4 and 7 have been taken by the authors.

Moreover, in order to collect representative samples of soil in each area, either in surface or in depth, soil is often collected in large excess compared to the analyzed quantity. For example*, consensus* on systematic or random sampling schemes requires a minimum number of sampling points, and generally, four samples for each geo-localized point can be enough (Chao and Thompson 2001). Of the total amount, 50% is generally stored in soil repositories, while only a minor quantity (~10%) is sent to the laboratory for analysis. Only some soil analysis are destructive (because they are carried out after sieving), whereas other analyses do not alter the soil quality and quantity and this makes possible restoring the sampled soil to the original site. Finally, the sampling procedure can also expose the soil to erosion, for instance, when a steep sampling site is left bare (that is, without the vegetal cover).

Usually, the "hidden erosion" does not heavy impacts the environment, because of its limited spatial and temporal extent and the small amounts of soil removed. However, when the soil is removed repeatedly on a large spatial scale, sampling may increase the erosion rates of the natural and other human-induced processes at the global scale. . It can be argued that the incidence of the "hidden erosion" is very low at the global time and spatial scales. However, it may accelerate the natural and anthropogenic erosion rates in degraded and delicate sites (e.g., forest ecosystems living on steep hillslopes, protected natural areas), aggravating local trends of soil consumption and degradation, and therefore this form of soil loss should be limited as much as possible.

In order to reduce the "hidden erosion" under tolerable limits, a decalogue to minimize this form of unwelcome soil degradation can be proposed as follows:

1. Avoid the soil transfer to the laboratory, preferring *in situ* experiments.
2. Use methods of soil analysis (e.g. visible and near infrared, vis–NIR), which are able to characterize the soil properties *in situ* (Viscarra Rossel et al. 2016), develop portable soil and plant testing kits as an alternative to laboratory, and use plant tests instead of chemical soil tests for fertility evaluation .
3. Use a composite sampling method instead of individual method, since the first one can reduce the amount of soil transferred to the laboratories and requires lower analytical costs.
4. Use augers (e.g., Shelby type) instead of shovels, because auger obtains soil samples from different depths by drilling, without having to dig a pit, and prepare soil samples in the field, where it is possible to return the non-analyzed particle fraction to the soil.
5. Minimize the size of drilling in soil genesis and classification studies, refill profile and reseed the created bare site by native plant seed after sampling, to prevent more erosion.

6. Take care (for instance, geologists and civil engineers) of making accessible the natural soil profiles, which are exposed to erosion from the infrastructure construction (e.g. roads) after slashing the layers, thus preventing digging new profiles.
7. Work in team to avoid repeated sampling of soil from the same location, and properly archive the exceeding soil sampled, which can be re-used by other researchers or for training activities in soil science.
8. Use pedotransfer functions and geostatistical techniques to design efficient sampling programs, and model the spatial pattern of soil properties, so that these models can be used in the interpolation of values in non-sampled locations, which reduce the need for a large number of sampling locations.
9. Quantify, record and communicate the volume of soil sampled for research purposes to national or cross-national authorities, as well as restore the residual soil after research in the original locations, if it is uncontaminated or does not pose risks for the humans and environment, or at least transfer the soil to greenhouses, gardens or parks.
10. Build a free online "Earth Soil Database" for re-using soils from a global archive with no need for re-sampling to evaluate soil properties.

Overall, thanks to this experimental investigation and the proposed decalogue, we wish that soil scientists and professionals are encouraged to work with an increased awareness of soil sensitivity to any disturbance factor, such as the "hidden erosion" is, in order to further preserve this precious resource for future generations.

References

Aksoy E, Yigini Y, Montanarella L (2016) Combining soil databases for topsoil organic carbon mapping in Europe. PLoS One 11:e0152098. https://doi.org/10.1371/journal.pone.0152098

Alewell C, Egli M, Meusburger K (2015) An attempt to estimate tolerable soil erosion rates by matching soil formation with denudation in Alpine grasslands. J Soils Sediments 15:1383–1399. https://doi.org/10.1007/s11368-014-0920-6

Banerjee S, Kirkby CA, Schmutter D, et al (2016) Network analysis reveals functional redundancy and keystone taxa amongst bacterial and fungal communities during organic matter decomposition in an arable soil. Soil Biol Biochem 97:188–198. https://doi.org/10.1016/j.soilbio.2016.03.017

Behera SK, Shukla AK (2015) Spatial Distribution of Surface Soil Acidity, Electrical Conductivity, Soil Organic Carbon Content and Exchangeable Potassium, Calcium and Magnesium in Some

Cropped Acid Soils of India. L Degrad Dev 26:71–79. https://doi.org/10.1002/ldr.2306

Beiranvand JP, Pourbabaee AA, Shirmardi SP, et al (2018) Symbiotic nitrogen fixation, phosphorus and potassium uptake capacity of a number of Soybean Mutant lines in a calcareous soil. J Agric Sci Technol 20:1555–1564.

Borselli L, Torri D, Øygarden L, et al (2006) Land Levelling. Soil Eros Eur 643–658. https://doi.org/10.1002/0470859202.ch46

Bruun TB, Elberling B, de Neergaard A, Magid J (2015) Organic carbon dynamics in different soil types after conversion of forest to agriculture. L Degrad Dev 26:272–283. https://doi.org/10.1002/ldr.2205

Bui EN, Hancock GJ, Wilkinson SN (2011) "Tolerable" hillslope soil erosion rates in Australia: Linking science and policy. Agric Ecosyst Environ 144:136–149. https://doi.org/10.1016/j.agee.2011.07.022

Buzmakov S, Egorova D, Gatina E (2019) Effects of crude oil contamination on soils of the Ural region. J Soils Sediments 19:38–48. https://doi.org/10.1007/s11368-018-2025-0

Capra GF, Tidu S, Lovreglio R, et al (2018) The impact of wildland fires on calcareous Mediterranean pedosystems (Sardinia, Italy) – An integrated multiple approach. Sci Total Environ 624:1152–1162. https://doi.org/10.1016/j.scitotenv.2017.12.099

Chao CT, Thompson SK (2001) Optimal adaptive selection of sampling sites. Environmetrics 12:517–538. https://doi.org/10.1002/env.477

Ebrahimi M, Sarikhani MR, Safari Sinegani AA, et al (2019) Estimating the soil respiration under different land uses using artificial neural network and linear regression models. Catena 174:371–382. https://doi.org/10.1016/j.catena.2018.11.035

FAO, (2019) Soil erosion: the greatest challenge to sustainable soil management. Rome. 100 pp.

FAO, ITPS (2015) Status of the World's Soil Resources (SWSR) - Main Report. Status World's Soil Resouces - Main Report Food Agric Organ United Nations Intergov Tech Panel Soils, Rome, Italy 650:608. https://doi.org/ISBN 978-92-5-109004-6

Farrell M, Jones DL (2010) Use of composts in the remediation of heavy metal contaminated soil. J Hazard Mater 175:575–582. https://doi.org/10.1016/j.jhazmat.2009.10.044

Farrell M, Perkins WT, Hobbs PJ, et al (2010) Migration of heavy metals in soil as influenced by compost amendments. Environ Pollut 158:55–64. https://doi.org/10.1016/j.envpol.2009.08.027

Goberna M, Podmirseg SM, Waldhuber S, et al (2011) Pathogenic bacteria and mineral N in soils following the land spreading of biogas digestates and fresh manure. Appl Soil Ecol 49:18–25. https://doi.org/10.1016/j.apsoil.2011.07.007

Guan ZH, Li XG, Wang L, et al (2018) Conversion of Tibetan grasslands to croplands decreases accumulation of microbially synthesized compounds in soil. Soil Biol Biochem 123:10–20. https://doi.org/10.1016/j.soilbio.2018.04.023

Hartemink AE (2019) Open access publishing and soil science – Trends and developments. Geoderma Reg 18:e00231. https://doi.org/10.1016/j.geodrs.2019.e00231

Houben D, Pircar J, Sonnet P (2012) Heavy metal immobilization by cost-effective amendments in a contaminated soil: Effects on metal leaching and phytoavailability. J Geochemical Explor 123:87–94. https://doi.org/10.1016/j.gexplo.2011.10.004

Jansa J, Erb A, Oberholzer HR, et al (2014) Soil and geography are more important determinants of indigenous arbuscular mycorrhizal communities than management practices in Swiss agricultural soils. Mol Ecol 23:2118–2135. https://doi.org/10.1111/mec.12706

Jiang Y, Chao S, Liu J, et al (2017) Source apportionment and health risk assessment of heavy metals in soil for a township in Jiangsu Province, China. Chemosphere 168:1658–1668. https://doi.org/10.1016/j.chemosphere.2016.11.088

Khan S, Reid BJ, Li G, Zhu YG, (2014) Application of biochar to soil reduces cancer risk via rice consumption: A case study in Miaoqian village, Longyan, China. Environ Int 68:154–161. https://doi.org/10.1016/j.envint.2014.03.017

Kirkby CA, Richardson AE, Wade LJ, et al (2013) Carbon-nutrient stoichiometry to increase soil carbon sequestration. Soil Biol Biochem 60:77–86. https://doi.org/10.1016/j.soilbio.2013.01.011

Laird D, Fleming P, Wang B, et al (2010) Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma 158:436–442. https://doi.org/10.1016/j.geoderma.2010.05.012

Lal R (2019) Accelerated Soil erosion as a source of atmospheric CO 2. Soil Tillage Res 188:35–40. https://doi.org/10.1016/j.still.2018.02.001

Le LTH, Dat ND, Minh NH, Nguyen KA (2019) Characteristics of PCDD/Fs in soil and sediment samples collected from A-So former airbase in Central Vietnam. Sci Total Environ 661:27–34. https://doi.org/10.1016/j.scitotenv.2019.01.163

Lv J (2019) Multivariate receptor models and robust geostatistics to estimate source apportionment of heavy metals in soils. Environ Pollut 244:72–83. https://doi.org/10.1016/j.envpol.2018.09.147

Montgomery DR (2007) Soil erosion and agricultural sustainability. Proc Natl Acad Sci U S A 104:13268–13272. https://doi.org/10.1073/pnas.0611508104

Nyiraneza J, Thompson B, Geng X, et al (2017) Changes in soil organic matter over 18 yr in Prince Edward Island, Canada. Can J Soil Sci 97:745–756. https://doi.org/10.1139/cjss-2017-0033

Panagos P, Borrelli P, Poesen J, et al (2016) Reply to the comment on "The new assessment of soil loss by water erosion in Europe" by Fiener & Auerswald. Environ Sci Policy 57:143–150. https://doi.org/10.1016/j.envsci.2015.12.011

Paz-Ferreiro J, Gascó G, Gutiérrez B, Méndez A (2012) Soil biochemical activities and the geometric mean of enzyme activities after application of sewage sludge and sewage sludge biochar to soil. Biol Fertil Soils 48:511–517. https://doi.org/10.1007/s00374-011-0644-3

Pelster DE, Chantigny MH, Angers DA, et al (2018) Can soil clay content predict ammonia volatilization losses from subsurface-banded urea in eastern Canadian soils? Can J Soil Sci 98:556–565. https://doi.org/10.1139/cjss-2018-0036

Pourbabaee AA, Soleymani A, Torabi E, Alizadeh H (2018) Degradation and Detoxification of Nicosulfuron by a Pseudomonas Strain Isolated from a Contaminated Cornfield Soil. Soil Sediment Contam 27:756–772. https://doi.org/10.1080/15320383.2018.1521784

Ruttens A, Adriaensen K, Meers E, et al (2010) Long-term sustainability of metal immobilization by soil amendments: Cyclonic ashes versus lime addition. Environ Pollut 158:1428–1434. https://doi.org/10.1016/j.envpol.2009.12.037

Sagarkar S, Nousiainen A, Shaligram S, et al (2014) Soil mesocosm studies on atrazine bioremediation. J Environ Manage 139:208–216. https://doi.org/10.1016/j.jenvman.2014.02.016

Shaddad SM, Buttafuoco G, Elrys A, Castrignanò A (2019) Site-specific management of salt affected soils: A case study from Egypt. Sci Total Environ 688:153–161. https://doi.org/10.1016/j.scitotenv.2019.06.214

Shaheen SM, Rinklebe J, Selim MH (2015) Impact of various amendments on immobilization and phytoavailability of nickel and zinc in a contaminated floodplain soil. Int J Environ Sci Technol 12:2765–2776. https://doi.org/10.1007/s13762-014-0713-x

Shahriari M, Delbari M, Afrasiab P, Pahlavan-Rad MR (2019) Predicting regional spatial distribution of soil texture in floodplains using remote sensing data: A case of southeastern Iran. Catena 182:104149. https://doi.org/10.1016/j.catena.2019.104149

Sharifi Z, Azadi N, Certini G (2017) Fire and Tillage as Degrading Factors of Soil Structure in Northern Zagros Oak Forest, West Iran. L Degrad Dev 28:1068–1077. https://doi.org/10.1002/ldr.2649

Shi P, Zhang Y, Li P, et al (2019) Distribution of soil organic carbon impacted by land-use changes in a hilly watershed of the Loess Plateau, China. Sci Total Environ 652:505–512. https://doi.org/10.1016/j.scitotenv.2018.10.172

Sollitto D, Romic M, Castrignanò A, et al (2010) Assessing heavy metal contamination in soils of the Zagreb region (Northwest Croatia) using multivariate geostatistics. Catena 80:182–194. https://doi.org/10.1016/j.catena.2009.11.005

Usikalu MR, Akinyemi ML, Achuka JA (2014) Investigation of Radiation Levels in Soil Samples Collected from Selected Locations in Ogun State, Nigeria. IERI Procedia 9:156–161. https://doi.org/10.1016/j.ieri.2014.09.056

Van de Voorde TFJ, Van der Putten WH, Bezemer TM (2012) The importance of plant-soil interactions, soil nutrients, and plant life history traits for the temporal dynamics of Jacobaea vulgaris in a chronosequence of old-fields. Oikos 121:1251–1262. https://doi.org/10.1111/j.1600-0706.2011.19964.x

Van de Voorde TFJ, van der Putten WH, Martijn Bezemer T (2011) Intra- and interspecific plant-soil interactions, soil legacies and priority effects during old-field succession. J Ecol 99:945–953. https://doi.org/10.1111/j.1365-2745.2011.01815.x

Verchot L V., Dutaur L, Shepherd KD, Albrecht A (2011) Organic matter stabilization in soil aggregates: Understanding the biogeochemical mechanisms that determine the fate of carbon inputs in soils. Geoderma 161:182–193. https://doi.org/10.1016/j.geoderma.2010.12.017

Verdejo J, Ginocchio R, Sauvé S, et al (2016) Thresholds of copper toxicity to lettuce in field-collected agricultural soils exposed to copper mining activities in Chile. J Soil Sci Plant Nutr 16:154–158. https://doi.org/10.4067/S0718-95162016005000011

Verheijen FGA, Jones RJA, Rickson RJ, Smith CJ (2009) Tolerable versus actual soil erosion rates in Europe. Earth-Science Rev 94:23–38. https://doi.org/10.1016/j.earscirev.2009.02.003

Viscarra Rossel RA, Behrens T, Ben-Dor E, et al (2016) A global spectral library to characterize the world's soil. Earth-Science Rev 155:198–230. https://doi.org/10.1016/j.earscirev.2016.01.012

Wang J, Luo Y, Teng Y, et al (2013) Soil contamination by phthalate esters in Chinese intensive vegetable production systems with different modes of use of plastic film. Environ Pollut 180:265–273. https://doi.org/10.1016/j.envpol.2013.05.036

Web of Science 2019. (www.webofknowledge.com), accessed 20 March 2019.

Zhang J, Wang Y, Liu J, et al (2016) Multivariate and geostatistical analyses of the sources and spatial distribution of heavy metals in agricultural soil in Gongzhuling, Northeast China. J Soils Sediments 16:634–644. https://doi.org/10.1007/s11368-015-1225-0

Zhang S, Huang Y, Shen C, et al (2012) Spatial prediction of soil organic matter using terrain indices and categorical variables as auxiliary information. Geoderma 171–172:35–43. https://doi.org/10.1016/j.geoderma.2011.07.012

Zhang X, Liu Z, Luc NT, et al (2015) Dynamics of the biological properties of soil and the nutrient release of Amorpha fruticosa L. litter in soil polluted by crude oil. Environ Sci Pollut Res 22:16749–16757. https://doi.org/10.1007/s11356-015-4874-z

Zhao K, Fu W, Qiu Q, et al (2019) Spatial patterns of potentially hazardous metals in paddy soils in a typical electrical waste dismantling area and their pollution characteristics. Geoderma 337:453–462. https://doi.org/10.1016/j.geoderma.2018.10.004