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Review

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The role of soils in regulation of freshwater and coastal water quality

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Water quality regulation is an important ecosystem service function of soil. In this study, the mechanism by which soil regulates water quality was reviewed, and the effects of soil management on water quality were explored. A scientometrics analysis was also conducted to explore the research fields and hotspots of water quality regulation of soil in the past 5 years. This review found that the pollutants entering the soil can be mitigated by precipitation, adsorption and desorption, ion exchange, redox and metabolic decomposition. As an optimal substrate, soil in constructed wetlands has perfect performance in the adsorption and passivation of pollutants such as nitrogen, phosphorus and heavy metals in water, and degradation of pesticides and emerging contaminants. Mangrove wetlands play an important role in coastal zone protection and coastal water quality restoration. However, the excessive application of agricultural chemicals causes soil overload, which leads to the occurrence of agricultural non-point source pollution. Under the dual pressures of climate change and food insecurity in the future, developing environmentally friendly and economically feasible sustainable soil management measures is crucial for maintaining the water purification function of soil by relying on the accurate quantification of soil function based on big data and modelling.

This article is part of the theme issue 'The role of soils in delivering Nature's Contributions to People'.

1. Introduction

Water quality is closely related to human health, and the contribution of soil to the regulation of freshwater and coastal water quality may be declining according to the assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [1]. Mineral particles of different sizes and organic matter constitute the main body of the soil structure, and different types of pores exist between soil particles or soil organic–inorganic complexes, making the soil play an important role in conserving water sources and regulating water quality [2]. Pollutants entering the soil can be reduced or eliminated by sedimentation, adsorption and desorption, ion exchange, oxidation–reduction and metabolic decomposition, among other processes, to improve water quality [3]. Forest, grassland and wetland soils can absorb and degrade pollutants caused by atmospheric deposition and sewage leakage to prevent these pollutants from directly entering the water body (figure 1). As a coastal wetland system, the mangrove system plays an important role in coastal zone protection and coastal water quality restoration [4]. Constructed wetlands (CWs) are multifunctional water purifiers, and previous studies have indicated that CW with soil as a substrate has a high removal efficiency for pollutants (such as nitrogen (N), phosphorus (P), chemical oxygen demand (COD), biochemical oxygen demand (BOD5)) in domestic sewage (figure 1).

With the rapid development of industry and agriculture, and the aggravation of human activities, a large number of pollutants enter the soil. When the input

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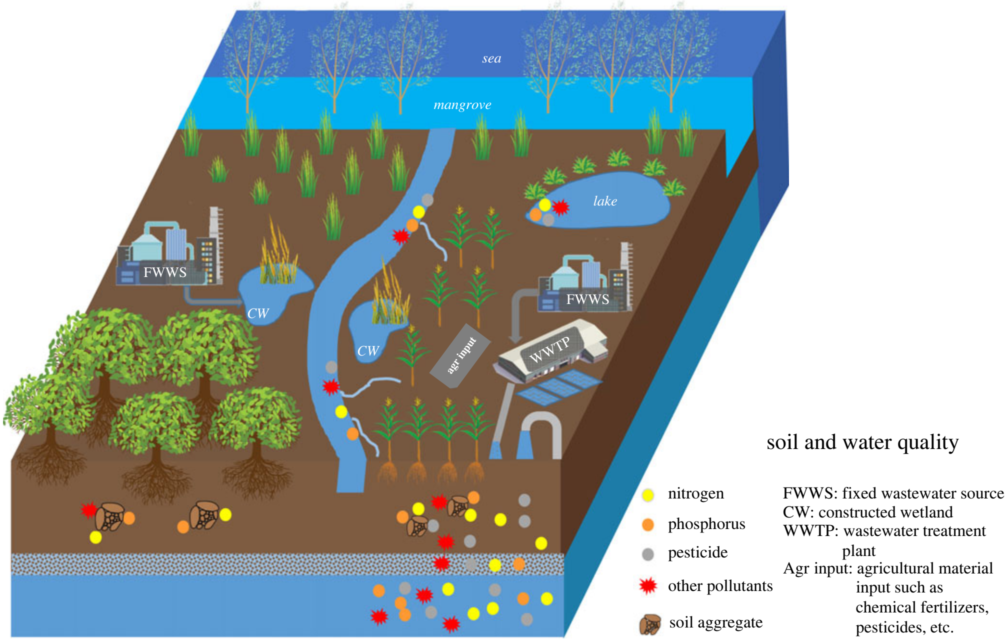

Figure 1. Schematic diagram of the role of soil in regulating water quality. (Online version in colour.)

pollutants exceed the self-purification capacity of the soil, the soil productivity declines, and the soil can become polluted (figure 1). Under the action of precipitation and irrigation, on the one hand, soil moisture can migrate longitudinally through soil pores into groundwater. In this process, the flow of soil moisture can remove chemical substances in the soil through physical and chemical processes, such as dissolution and leaching. Mineral weathering elements as well as natural and artificial organic compounds are transported into the water body [5]. On the other hand, precipitation can bring soil particles and soluble substances into surface water through surface runoff, thus affecting water quality [6]. Globally, agriculture is considered to be the largest source of non-point source (NPS) pollution in surface and groundwater systems. Approximately 3–4 million tons of P_2O_5 are transported from soil to water annually worldwide [7], and 29.1–67.5 and 25–45.9%, respectively, of total N and P flowing into rivers are from farmland [8]. Up to 90 types of pesticides were detected in the water bodies of the Strymonas Basin in Greece, and the maximum concentrations of chlorpyrifos, fumaric acid and terbutin far exceeded the maximum allowable concentration stipulated in the European Union Drinking Water Directive [9]. Therefore, soil management is of great significance in water quality control.

A scientometrics analysis through Citespace 5.7.R2 (http://cluster.ischool.drexel.edu/~cchen/citespace/download/) was conducted to explore the research fields and hotspots of water quality regulation of soil in the past 5 years (electronic supplementary material). Based on the soil–water interaction under natural and artificial management conditions, this review describes the mechanism of soil regulation of water quality, discusses the factors affecting the function of soil in regulating water quality and explores sustainable soil management for water quality improvement.

2. Mechanism of water quality regulation by soil

Soil regulates and stores water through infiltration and percolation. Infiltration refers to the process of water entering the soil through the pores of the topsoil, and the process of infiltration and diffusion of water from the surface layer to the deep layer along the pores is termed percolation. These two processes significantly reduce surface runoff, alleviate the collection of precipitation in the rainy season and exert a significant impact on soil flow and groundwater recharge [10].

Forest and grassland ecosystems minimize surface runoff and increased soil water storage through vegetation (figure 1). For example, grassland and scrubland prevent rain splashing effectively and reduce soil erosion by covering the grass and litter layers near the soil surface [11]. Soil erosion caused by land-use change has been a research hotspot in recent years (figure 2*a*), and soil erosion has a significant negative impact on water quality, such as an increase in water turbidity and chemical substance concentrations [12]. The increase in soil erosion rate caused by natural deforestation has a significant downstream impact on freshwater and estuarine environments through changes in hydrological processes, as well as the direct impact of sediments on freshwater species [13]. By combining the existing soil erosion and water quality models, logging above 400 m upstream of Kolombangara Island in the Solomon Islands is directly related to river water quality [14]. Recently, the public has been paying greater attention to the effects of forest degradation on human health. There is a close relationship between the decrease in forest coverage in the upstream watershed and the high incidence rate of disease outbreaks caused by aquatic pathogens [15]. In addition to external forces such as vegetation and meteorological conditions, soil properties (soil texture, bulk density, water content, cohesive force, aggregate and organic matter content) significantly affect the soil separation process. Wischmeier *et al.* [16] proposed an evaluation index system covering five indexes: silt + very fine sand content, sand content, organic matter content, soil structure grade and soil permeability grade. The evaluation index system greatly improved the prediction accuracy of the soil erosion model. The soil property-based indexes have certain regional characteristics, and the responses of the indicators may vary in different regions. Bonilla & Johnson [17] found that there was no correlation between soil erodibility and soil organic matter, although many studies

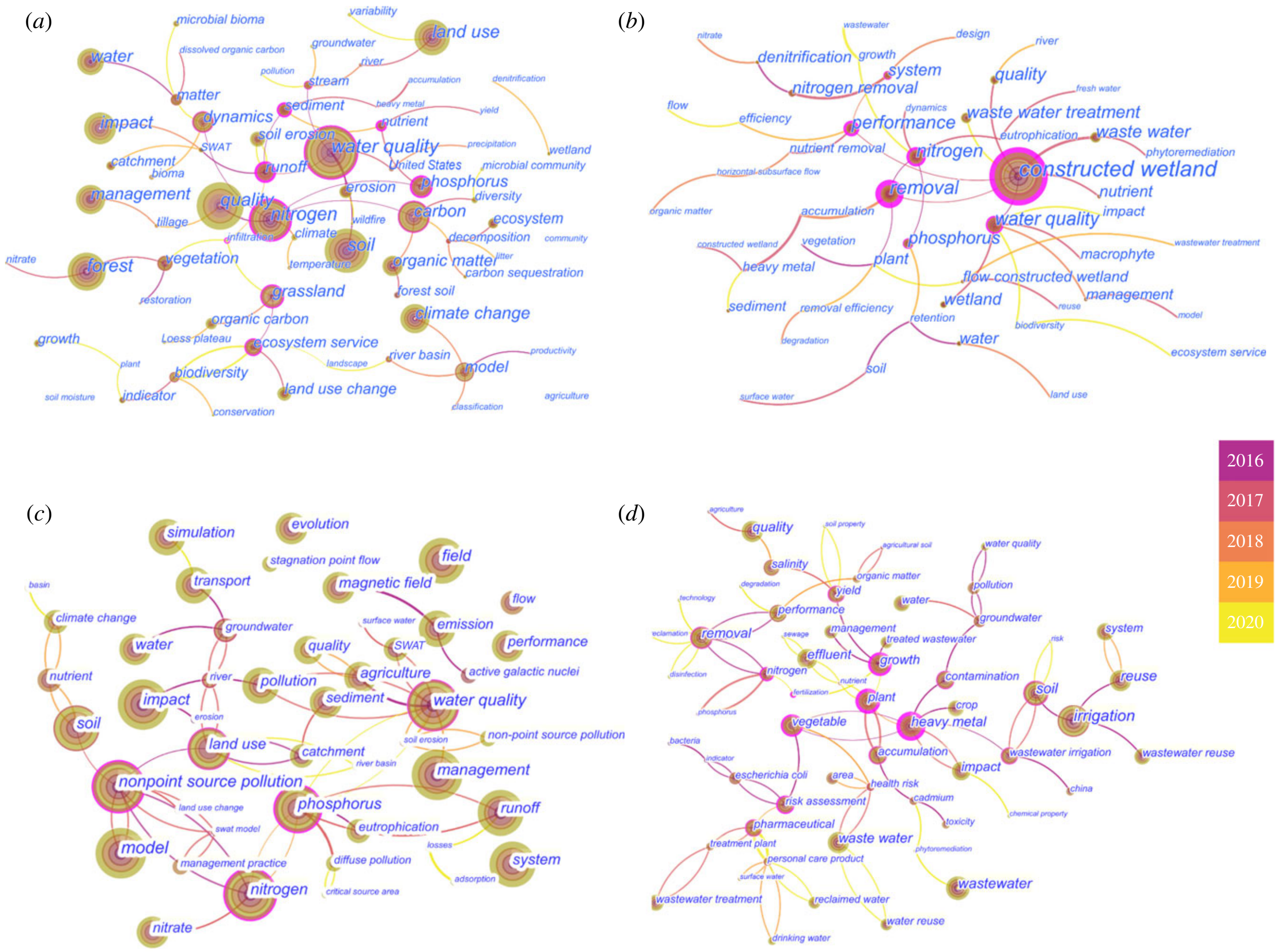

Figure 2. Frequency and centrality of keywords in published papers during 2016–2020. (*a*) Water quality and soil of forest, grassland and natural wetland; (*b*) water quality and soil of constructed wetland; (*c*) agricultural NPS pollution and (*d*) WWI. SWAT, soil and water assessment tool. (Online version in colour.)

have found significant positive correlations. The soil erodibility index was positively correlated with soil bulk density and negatively correlated with soil organic carbon and clay content [18]. In addition, soil aggregates, as the basic unit of soil structure, have a significant impact on soil erodibility and can be used as an important indicator to characterize soil erodibility [19]. Relevant studies have found that aggregate content in soil, size, stability index, mean weight diameter (MWD) and mean geometric diameter were significantly related to soil erodibility [19]. For example, Ayoubi *et al*. [18] found that the soil erodibility index was significantly negatively correlated with MWD.

The rate of water percolation mainly depends on the size of the non-capillary pores in the soil. Under the same conditions, the larger the non-capillary porosity of the soil, the better the permeability of the soil and the lower the surface runoff [20]. The effect of the soil layer on water quality regulation is mainly manifested in the absorption of ions by litter and soil colloids, the decomposition of compounds and the absorption of ions by microorganisms, physical and chemical adsorption, and precipitation of metal elements by soil [21]. For example, only a small amount of runoff was formed on a grassland in Miyagi Prefecture, Japan, after snow melting, and the concentration of radioactive caesium in runoff samples was lower than the standard limit value of drinking water in Japan, which indicated the protective effect of natural ecosystems on water quality safety [22]. Forests have also been found to purify wastewater from cities, industries and agriculture through soil infiltration, and this type of system is called a forest water reuse system. McEachran *et al*. [23] found that large amounts of pharmaceuticals and personal care products were removed from wastewater by a forest water reuse system before reaching the groundwater and watershed outlet.

The contribution of natural wetlands to water purification has been widely studied, and wetland soil/sediment plays an important role in water quality regulation because of the long-term retention of chemical elements in soil/sediment (figure 1) [24]. The adsorption of heavy metals by clay and organic matter and the chelation of organic matter were observed in the surface sediments of the Yellow River Estuary and adjacent sea areas [25]. The fixation of heavy metals in mangroves may also be related to the presence of glycoproteins and microorganisms. Wen *et al*. [26] showed that the large distribution of glomalin-related soil protein (GRSP) in sediments and suspended solids improved the fixation potential of heavy metals and metalloid arsenic in mangrove aquatic ecosystems, and GRSP is a glycoprotein with strong heavy metal chelating capacity. Kayalvizhi & Kathiresan [4] also found the potential of *Bacillus marisflavi* to remove heavy metals and solubilize zinc. Denitrification is an important process in wetland nitrogen removal [24] (figure 2*b*). The denitrification rate of salt marsh was positively correlated with soil moisture, soil organic matter and nitrate content, and negatively correlated with soil pH and salinity [27–29]. Anammox also plays an important role in N removal in estuaries and coastal wetlands. In general, an increase in salinity increases the activity and abundance of anammox bacteria, but high salinity causes physiological stress in the short term [29]. Freeze–thaw cycles have significant effects on the biogeochemical processes of wetland soils in the middle and high latitudes. The freeze–thaw process causes great damage to water-stable aggregate components larger than 2 mm, increased water stable aggregate (WSA) components smaller than 0.053 mm and significantly increased the contents of ammonium and nitrate, respiration rate and total nitrification rate [30]. Human activities that affect the water, sediment and nutrient loads of wetlands may significantly alter wetland plant and microbial communities. Therefore, understanding the mechanisms of biogeochemical cycles in wetlands is of great significance for wetland restoration and protection.

3. Water quality degradation owing to improper soil management

The harmful effects of deforestation, overgrazing, tillage and inappropriate agricultural practices on soil erosion are well known, and the acceleration of soil erosion has been the main threat to soil safety [31]. Compared with 2001, global soil erosion increased by 2.5% in 2012 to 35.9 Pg [32]. It is generally believed that soil erosion can induce soil nutrient deficiency and land degradation, and soil erosion also leads to many environmental problems, such as sedimentation, siltation and eutrophication of water bodies or the aggravation of floods. For example, it was found that 45.9% of the decrease in water turbidity in the Yangtze River region was related to the reduction of soil erosion, while 42.5% of the increase in water turbidity may be affected by the intensification of soil erosion [33]. Nutrients, heavy metals and chemicals can also migrate with soil particles, eventually leading to the eutrophication of water bodies and destruction of fragile aquatic ecosystems.

Owing to the extensive use of chemical inputs, pollutants enter the surface and groundwater through runoff and leaching which is called agricultural non-point source (NPS) pollution (figure 1) [34]. In 2018, the total input of N, P and pesticides in global agriculture was approximately 108.7, 40.6 and 4.1 Mt, of which the consumption of N and P fertilizer in China, India, the USA, Brazil and Pakistan accounted for more than 60%, and the consumption of pesticides in China, the USA, Brazil, Argentina and Canada accounted for 38.5% (figure 3) [35]. The total consumption of nitrogen and phosphorus fertilizers in China and India has been on the rise, but the consumption in China has shown a downward trend in the past 5 years, which is related to a series of measures taken by the Chinese government, such as zero growth of chemical fertilizer and soil testing and formula fertilization projects. Nevertheless, the use of pesticides in China has increased rapidly, although it has stabilized in the past 5 years (figure 3).

According to the Environmental Protection Agency, agricultural NPS is the largest source of surface water pollution, contributing two-thirds of the total pollution load. In some European countries (including Denmark, Norway, Sweden, The Netherlands, Finland and the UK), agriculture contributes 50–90% and 30–50% of the total N and P loads in the water environment, respectively [36]. According to a 2017 survey, pollutants discharged from agricultural sources in China had a great impact on the water environment, and the N and P loads from cropland accounted for 24% of the total [37].

The precise quantification of pollutant losses from site to regional scale is required for NPS control approaches, and the estimation of N and P losses has become a significant research interest in recent years (figure 2*c*). Mekonnen & Hoekstra [38] estimated the anthropogenic N and P loads of global freshwater at a spatial resolution of 5 × 5 arc minutes from 2002 to 2010. Based on the long-term balance of soil N, it was found that crop planting contributed three-quarters of the global load, and the amount of P loss from crop planting contributed 38% of the total load using the erosion-runoff-leaching fraction, which considered the soil texture, soil erosion vulnerability, soil P content, rainfall intensity and management measures. The loss of farmland with different crop types is different (table 1). In general, the nutrient loss rates in the paddy rice planting season were higher than those in other crops, and the loss rates from runoff and leaching in vegetable fields were also obvious (table 1). Based on data from the literature on N and P loss in open field vegetable systems in China from 1990 to 2018, it was found that the loss of N and P in the fruit vegetable system accounted for 13.1% and 3.95% of the fertilizer amount, while the loss rates of leaf vegetables were 4.63% and 2.57%, and stem/root vegetables were only 1.85% and 0.07%, respectively [39]. Redundancy analysis indicated that the contribution of the soil N pool to N loss was greater than that of fertilizer input, while the contribution of P input to P loss was greater than that of the P pool in soil [39].

As a special hydrological system, the karst system is defined by the uneven distribution of high-permeability dissolution channels developed in carbonate rocks and the connectivity of these channels with the surface, in which nutrient leaching is unique. A survey of P transfer from high-P agricultural soil to karst aquifer in Mayo County, Ireland, revealed a low concentration of total P in groundwater [44]. Jarvie *et al.* [45] found that 90% of the annual dissolved P flux remained on the surface of 2–3 m of the karst, which may reduce the risk of losses caused by acute sudden storms of P. However, subsequent P reactivation and transfer may provide a long-term source of residual P transported through springs to surface water [46].

As estimated, 1–6% of pesticides may be lost to the water environment through runoff and drainage, depending on the slope of the field, agronomic measures, the existence of underground drainage ditches and the amount and time of rainfall after application [47]. Adsorption, degradation and migration are key processes that determine the fate of pesticides in the environment [47]. Adsorption is the result of the interaction between the pesticide and soil colloids, which can be reversible or irreversible. However, water movement in soil is the main mechanism of pesticide transfer to the surface and groundwater [48]. The hypothesis of pesticide migration in soil includes preferential flow, co-transportation with colloidal substances and the combination of these two processes [49]. The physico-chemical properties of pesticides, volatilization rate, soil texture, soil organic matter content and permeability, root uptake, pesticide application method/dose and climate change were the key factors affecting pesticide leaching [50]. In addition to clay content and other characteristics of soil, the amount of organic C was considered to be the main factor leading to the adsorption, degradation and migration of pesticides [51]. The adsorption capacity of organic matter was strong, and the increase in organic matter can lead to changes in the soil pore structure and affect water movement; meanwhile, dissolved organic matter and pesticides compete for adsorption

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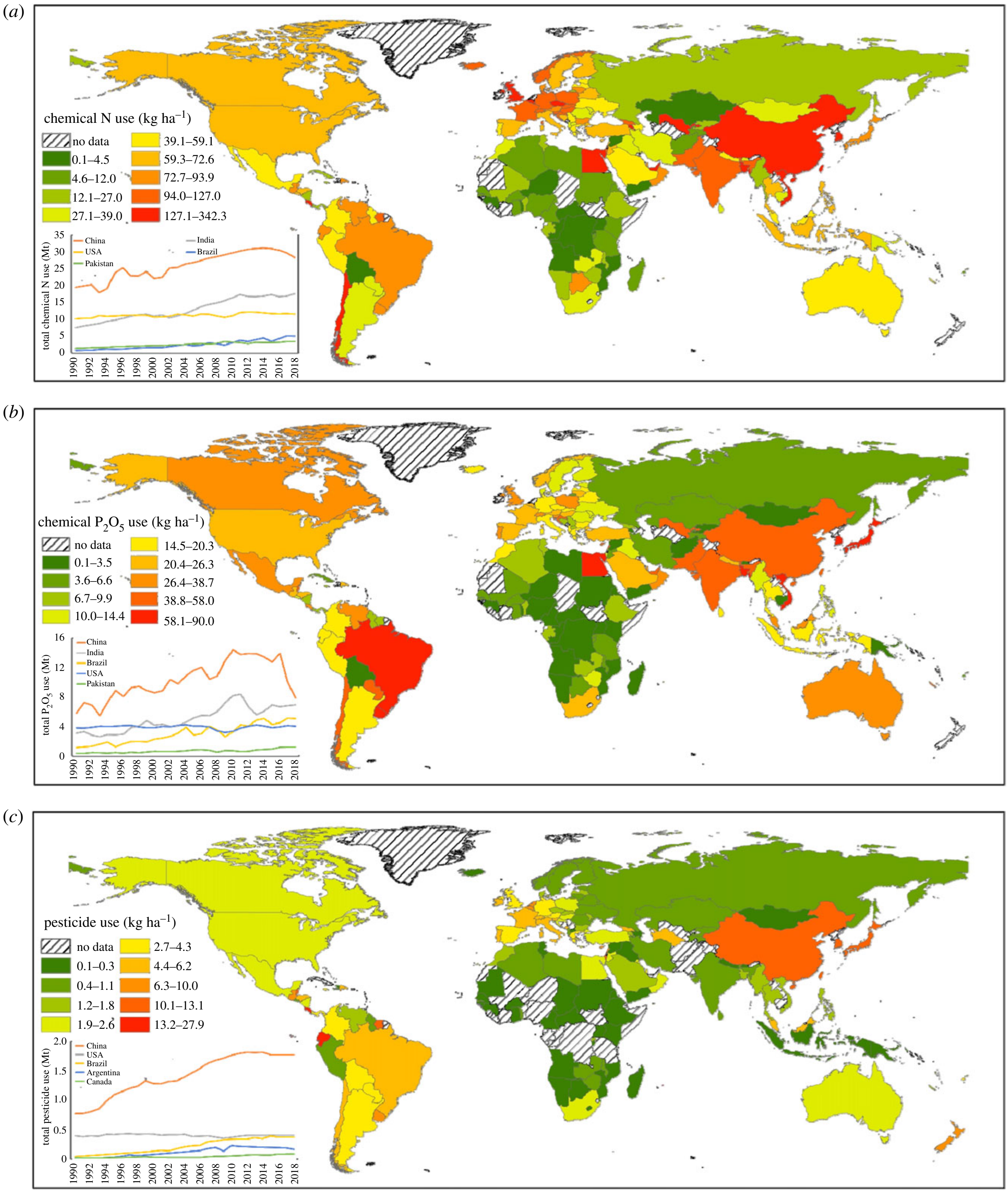

Figure 3. Spatial distribution of chemical (*a*) N, (*b*) P and (*c*) pesticide application rates per hectare in 2018 (mapping data were collected from FAOSTAT [35]). (Online version in colour.)

sites. The addition of organic materials can also affect the activity of soil microorganisms, which may affect pesticide degradation.

Model application plays an important role in the evaluation and prediction of NPS and is one of the research hotspots (figure 2*c*). Among the models, the soil and water assessment tool (SWAT) was undoubtedly the most widely used (figure 2*c*). The SWAT is a large- and medium-scale watershed distributed model with a physical mechanism developed by the USDA in 1993 [52]. This model aims to assist water resource managers in assessing water supply and NPS in large basins [53]. The SWAT uses a large amount of basic watershed data such as meteorological data, soil data, topography, vegetation coverage and land management information as inputs to directly simulate physical processes, including water movement, sediment movement, plant growth processes and nutrient circulation. However, the model parameters need to be calibrated to improve the model efficiency when simulating NPS in different countries or regions. For example, Abbaspour *et al.* [54] combined calibration tools with high spatial resolution data to calibrate the N load of rivers and the production of wheat, corn and barley, and the final calibrated model and results provide information support for the European Water Framework.

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Table 1. Examples of runoff and leaching loss rates of N and P loss from the cultivation of different crops.

location	crop type	N loss rate	P loss rate	reference
13 provinces in China	paddy rice	8.79% (runoff)	1.49% (runoff)	[39]
	upland crops	5.32% (runoff)	1.91% (runoff)	
	vegetable	6.27% (runoff)	4.08% (runoff)	
Jeollabuk-do, South Korea	paddy rice	11.3–19.1% (surface runoff)	0.5–1.7% (surface runoff)	[40]
		0.2–0.8% (subsurface loss)	0.02–0.04% (subsurface loss)	
Colombia, USA	potato	54.7% (runoff and leaching)	0.03% (runoff and leaching)	[41]
Ballantrae, New Zealand	pasture	15.4% (runoff and leaching)	2.06% (runoff and leaching)	[42]
Georgia, USA	cotton	8.37–8.71% (runoff)		[43]

Table 2. Examples of the removal efficiency of different pollutants in constructed wetlands. FIB, faecal indicator bacteria.

location	type of constructed wetland	pollutant and removal rate	reference
Dali, China	free surface flow CW	63.7% and 64.0% of N and P	[55]
Hangzhou, China	free surface flow CW	45% of N, 57% of NO_3^-–N and 78% of P	[57]
Piracicaba, Brazil	vertical subsurface flow CW	93% of P	[58]
Florida, USA	free surface flow CW	68% of faecal coliform, 42% of P, 35% of N and 23% of Zn	[59]
Strasbourg, eastern France	pond followed by a vertical subsurface flow CW	100% of dissolved Cr, Co, Cu, Pb and Zn, 100% of particulate Cu, Pb and Zn, 97% of particulate Cr and 98% of particulate Co	[60]
Catalonia, Spain	free surface flow CW	73% of pesticides, 62% of contaminants of emerging concern	[61]
Tucson, Arizona, USA	vertical subsurface flow CW	98.8%, 98.2% and 95.2% of the total coliform, FIB and *E. coli* phage	[62]
Ireland	free surface flow CW	5%, 60%, 31% and 86% of Cd, Cu, Pb and Zn	[63]

As shown in figure 3, there were significant differences in N, P and pesticide input per unit area between different countries, indicating large discrepancies in management levels. The technologies for agricultural NPS prevention include source control, process interception and end purification. Source control mainly achieves the goal of reducing the generation and discharge of pollutants by optimizing agricultural management, such as integrated water and fertilizer management technology, which means that measures are taken to intercept, degrade or use the migration pathways of pollutants, thereby reducing the discharge of pollutants into water bodies; end purification refers to the prevention technology of pollution treatment and purification by taking corresponding engineering measures according to the pollution type, such as setting the CW as a buffer zone in low-lying areas of large-scale farmlands [36].

4. Measures for water purification by soil

CW engineering developed in the 1970s is an effective measure for purifying water quality. CWs are constructed and supervised ecosystems that reflect the characteristics of natural wetlands (figure 1). They make full use of the physical, chemical and biological cooperation of the substrate–microorganism–plant complex ecosystem to achieve wastewater purification. The removal mechanism of pollutants by CW generally includes adsorption and sedimentation of the substrate, degradation and passivation of microorganisms, enrichment and degradation of aquatic plants, and degradation of biofilm [55]. The substrate is an important factor affecting hydraulic performance, plant growth and system blockage in CWs [56]. Wang *et al.* [56] used the indexes of contaminant removal capacity, availability, likely cost, permeability and reusability to score different substrates of CWs and found that both soil/sediment and gravel, with advantages in cost and efficiency, had the highest score.

The subjects related to the removal of N and P in water by CW have a high centrality as hotspots of concern (figure 2*b*). CW had a significant effect on nutrient removal (table 2). Microbial denitrification and anaerobic ammonia oxidation play major roles in removing N from CW soil, followed by soil adsorption and plant absorption [64]. The P retention capacity of CW soil was related to the content of amorphous and weakly crystalline Fe and Al, and the content of organic matter [65]. The properties of wastewater can affect the removal of nutrients from CW. For example, CWs are often used to treat saline wastewater in coastal cities. Laboratory-scale CWs with filter layers of soil, zeolite, anthracite and gravel had removal rates of 73%, 77% and 66% for total N, ammonium and nitrate at 0 and 0.5% salinity, respectively, while the rates decreased to 44%, 59% and 49%, respectively, at 2% salinity [66].

The removal efficiency of heavy metals varies greatly with the types of CWs, and the vertical subsurface flow CW had a higher removal efficiency than the free surface flow

CW (table 2). Potential removal processes for divalent cation heavy metals include particle sedimentation, precipitation (especially precipitation with sulfides under anaerobic conditions), co-precipitation, sorption (cation exchange) and plant uptake [67]. It was also found that metal accumulation in vegetation was almost negligible compared with that in the sediment [63].

Soil/sediment in the CW can remove pesticides by adsorption and microbial degradation (table 2). Pesticides have been proven to be removed by biodegradation and photodegradation, but in some cases, hydrolysis or adsorption of organic matter can also play a role [68]. However, the latter was less likely because most insecticides were polar. Microbial degradation of pesticides is essentially an enzymatic reaction, which refers to the process by which microorganisms use pesticides as food substrates to promote their own growth while promoting pesticide degradation. Microorganisms can promote the degradation of pesticides through enzymatic reactions and can also affect degradation by changing the environmental conditions of pesticide degradation [69]. Vallée *et al*. [70] found that the presence of plants in the CW can increase the adsorption capacity of soil/sediment to pesticides, which was owing to the fact that plant roots can absorb pesticides, and the presence of plants increased the retention time of water and prolonged the reaction time between soil/sediment and pesticides.

Recently, the removal of emerging pollutants from water by soil/sediment in CW has become a hot topic. CWs with soil/sediment substrates can effectively remove drugs, dyes, halogenated flame retardants and many other organic pollutants (table 2). Hussain *et al*. [71] found that the removal efficiency of sandy soil was higher than that of sandy loam because more water could be immersed in sand, which provided more interaction between drugs and the matrix. CW can also effectively remove faecal indicator bacteria (FIB) and antibacterial resistance genes in wastewater (table 2). The removal mechanism of FIB in CWs was that FIB was absorbed by soil particles in the water and fixed as the soil particles settled [72]. Root exudate/rhizosphere microorganisms may also have adverse effects on the survival of faecal microorganisms [73]. According to an overview by Alexandros & Akratos [74], the removal rate of pathogens in CWs can be as high as 99%. The removal of pathogenic microorganisms in CWs was accomplished by the combination of chemicals (such as oxidation, sunlight and ultraviolet radiation, exposure of plant biocides, adsorption of organic matter and biofilm), physical processes (such as filtration and precipitation) and biology (such as predation, biodegradation and antibiotics).

The long-term operation of CWs will inevitably lead to the significant accumulation of pollutants in soil and sediment, which may be re-released in the future and bring risks. Therefore, it is necessary to maintain and update the wetland systems. The application of phytoremediation in CW, the role of biodiversity in the purification of water and the application of these models have attracted more attention (figure 2*b*).

As an important alternative water resource, wastewater can be used in agriculture to compensate for water shortages. Wastewater irrigation (WWI) means that the wastewater is re-used for irrigation after being treated to meet the water quality requirements of the corresponding crops (figure 1). This practice avoids the discharge of pollutants into the water body. Moreover, because crops, microorganisms in the soil, and the soil itself can purify wastewater, after secondary treatments such as oxidation ponds and oxidation ditches, the farmland carries out stronger physical, chemical and biological purification of the treated wastewater, thereby increasing the supply of groundwater [75]. This process is equivalent to a higher level of wastewater purification, reducing the number of stages and the complexity of treatment, thus reducing the cost. WWI has been employed for over 100 years worldwide. In Europe, the USA and China, the reuse rate of wastewater increases by 10–29% every year, and Australia has reached a reuse rate of 41% [76]. Israel is a leader in WWI, accounting for more than 40% of the agricultural water flow from recycled wastewater [77]. As shown in figure 2*d*, the centrality of soil removal, heavy metals, growth and risk assessment associated with WWI was the highest, which indicates that in recent years researchers have focused on the positive role of WWI in crop production and the importance of soil in water quality regulation, and also found the environmental risks—such as heavy metal enrichment that WWI may bring.

The treated wastewater contained a variety of components that were intercepted by the soil and purified, and the clean leachate increased the recharge of groundwater. For example, Nzediegwu *et al*. [78] used wastewater containing heavy metals for irrigation, and no heavy metals were detected in leachate. Some studies have shown that there was no difference in bacteria and pathogens in soil and vegetables between those irrigated with clean water and or with treated wastewater, while the clay in soil had a special stabilizing effect on the existence of potential microbial pathogens [79]. The treated wastewater contains growth-promoting components, thus promoting the growth of crops [80]. Compared with clean water irrigation, WWI can reduce fertilizer consumption by 45% for wheat and 94% for Alfalfa [81]. However, Zolti's experiment on WWI in Kiryat gat, northern Negev, Israel, showed that the yield of tomato and lettuce would be reduced by using treated tertiary wastewater, which may be related to the increase in soil electrical conductivity [82]. Of course, the impact of WWI on yield was complicated by water quality, soil properties, crop types, agricultural practices and environmental conditions.

Untreated or partially treated wastewater has been used to irrigate over 20 million ha of land worldwide [81]. Without proper management, pathogenic microorganisms and chemical pollutants (e.g. engineering nanoparticles, salts, heavy metals and antibiotics) in wastewater may pose serious risks to human health and the environment. Ibekwe *et al*. [83] reported that treated sewage contained a certain amount of potential pathogens, which would affect soil health and food safety; however, the application of biochar could mitigate the microbial pollution caused by sewage irrigation [50]. A study indicated that biochar application could also reduce the contents of Cd and Zn in the pulp and peel of tuber [78]. A review by Poustie *et al*. [77] found that the positive effects of wastewater nutrients on crop production may be offset by the negative effects of high salt concentrations. An accumulation of tetracycline, sulfamethoxazole and resistance genes was found in the soil after long-term irrigation with domestic sewage and fishpond wastewater, and the content in soil irrigated by fish pond wastewater was higher than that irrigated by domestic sewage [84].

In view of this, formulating a reasonable WWI strategy is necessary for water purification and safe production. In the past 2 years (figure 2*d*), researchers have focused on the risk of WWI on human health, the development of WWI technology (such as combining with phytoremediation) and the assessment of soil properties suitable for WWI. First, wastewater should be treated to fit the quality standard. Second, the suitability of the WWI should be evaluated. For example, WWI was not suitable in highly permeable soils, high groundwater levels, aquifer outcrops and centralized drinking water sources. Studies have shown that sandy clay loam is more resistant to soil erosion caused by WWI than loam [85]. Moreover, suitable irrigation techniques can be used to reduce the risks. Flood irrigation may seriously pollute the entire farmland, and drip irrigation is the most environmentally friendly method [81]. Finally, the groundwater affected by WWI should be monitored frequently to determine the performance of the soil as a biogeochemical filter.

5. Conclusion

Soil has a positive impact on water quality purification through adsorption and desorption, ion exchange, redox and metabolic decomposition, whether in natural ecosystems such as forests, grasslands, and natural wetlands or CWs and farmland irrigated by wastewater. However, changes in land-use patterns and high intensities of agricultural soil use have a negative impact on water quality through soil erosion, dissolution and leaching of nutrients and other pollutants. The development of an environmentally friendly sustainable soil management mode for the efficient use of resources is crucial for maintaining and improving the ecosystem service function of soil for water quality regulation.

6. Outlook

The following issues should be addressed in future research according to this review. First, climate change has frequently appeared as a keyword in studies on the relationship between soil and water quality, indicating that researchers currently focus on the impact of climate change on the service function of soil ecosystems and the challenges that climate change will bring to sustainable soil management in the future. A method to improve the accuracy of climate change predictions is suggested. Second, big data and modelling will undoubtedly play an important role in future research and management efforts. For example, the SWAT model was coupled with the groundwater model (MODFLOW) to quantify the long-term impact of the best management scheme on water quality affected by soil erosion and nutrient leaching at high spatial resolution [86]. In addition, the localization of model parameters and the construction of regional characteristic models should be carried out. Third, the construction of a soil sustainable management model is necessary to ensure the sustainable development of the economy and environment. The role of soil aggregates and biochar amendment in water quality regulation has been investigated, providing new ideas for sustainable soil management. A study has combined the watershed model with the cost–benefit curve to quantify the reduction effect of different best management practices on N and P loads and the cost to be paid, and finally determined the best scheme suitable for the basin [87]. Therefore, coupling the environmental model with the economic model to identify the optimal mode for specific regions is also a future research trend.

Data accessibility. This article has no additional data.

Authors' contributions. K.C. conceived of the study, coordinated the study and drafted the manuscript; X.X. collected data and material; L.C. collected material and helped draft the manuscript; Y.L. collected material and helped draft the manuscript; J.Z. conceived of the study, designed the study and drafted the manuscript; W.W. collected material; J.S. collected material; G.P. coordinated the study and helped draft the manuscript. All authors gave final approval for publication and agree to be held accountable for the work performed therein.

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