Soil Protection in Floodplains—A Review

Mariam El Hourani * and Gabriele Broll

Abstract: Soils in floodplains and riparian zones provide important ecosystem functions and services. These ecosystems belong to the most threatened ecosystems worldwide. Therefore, the management of floodplains has changed from river control to the restoration of rivers and floodplains. However, restoration activities can also negatively impact soils in these areas. Thus, a detailed knowledge of the soils is needed to prevent detrimental soil changes. The aim of this review is therefore to assess the kind and extent of soil information used in research on floodplains and riparian zones. This article is based on a quantitative literature search. Soil information of 100 research articles was collected. Soil properties were divided into physical, chemical, biological, and detailed soil classification. Some kind of soil information like classification is used in 97 articles, but often there is no complete description of the soils and only single parameters are described. Physical soil properties are mentioned in 76 articles, chemical soil properties in 56 articles, biological soil properties in 21 articles, and a detailed soil classification is provided in 32 articles. It is recommended to integrate at least a minimum data set on soil information in all research conducted in floodplains and riparian zones. This minimum data set comprises soil types, coarse fragments, texture and structure of the soil, bulk density, pH, soil organic matter, water content, rooting depth, and calcium carbonate content. Additionally, the nutrient and/or pollution status might be a useful parameter.

Keywords: soil protection; restoration; floodplain; soil bioengineering

1. Introduction

Floodplains and their soils are an important part of the river system and fulfil important ecological, economic, and social functions like natural flood protection, sustaining high biological diversity or filtering and storing water [1,2]. Floodplains can be regarded as hotspots for biogeochemical processes such as denitrification [3,4] or eutrophication [1]. Floodplains are regularly flooded by the adjacent river [5]. Thus, the lateral connection to the river is essential for the functioning of a floodplain [6]. The riparian zone is characterized as the zone between the low-water and the high-water mark [7,8]. Both represent ecotones at the transition between aquatic and terrestrial environments [6]. Riparian zones hence are the last point in the landscape where nutrients can be intercepted before they enter the rivers [9]. Often, the terms floodplain and riparian zone are treated as synonyms in the literature or are not clearly differentiated from each other. Floodplains do not only provide a wide range of ecosystem services, but also are one of the most threatened ecosystems in the world [2,10]. Today, many floodplains worldwide are degraded because of high hydromorphological and diffuse pollution pressures, dam building, diversion, or abstraction of water or clearing of land and cannot deliver the ecosystem services in the same extent as a natural floodplain [1,11,12]. Approximately 70–90% of Europe’s floodplains are degraded [12]. The dynamic flow regime of the river is essential not only to the river functioning, but also to the ability of the floodplain to provide ecosystem services [11].

Soils in the floodplains and the riparian zone are strongly influenced by the adjacent river. These soils are often called alluvial soils as their physical, morphological, chemical, and mineralogical properties are influenced by the alluvial parent material derived from...
the river. The development of alluvial soils strongly depends on the flow regime [13]. Sediment transport and deposition are characteristic processes for the development of alluvial soils [14]. Recent alluvial soils are often classified into the reference soil group of Fluvisols in the world reference base for soil resources or into the order of Entisols (suborder Fluvents) in the US soil taxonomy [13,15,16]. Older alluvial soils can be transformed into multiple different soil types [13]. Fluvisols are characterized by fluvic material and can occur on any continent and in any climate zone. They occupy less than 350 million ha worldwide [15]. Naturally Fluvisols are fertile soils having been used by humans since the prehistoric times. Soils in the floodplain or riparian zone influenced by groundwater and showing classic gleyic properties can also be classified as Gleysols. These are soils that typically occupy low positions in the landscape with high groundwater tables and can also occur on any continents and in any climate zones. The parent material on which Gleysols develop can be a wide range of unconsolidated deposits, but often they also develop on fluvial, marine, or lacustrine deposits like Fluvisols [15]. Through their special characteristics these alluvial soils are able to provide information on past and present fluvial dynamics and ecosystem structure through their morphology [17,18].

In the past decades, floodplain management has changed from river control to the restoration of floodplains and rivers which can reduce the pressures and restore related functions and services [1,2,10,19–21]. In Europe, several directives like the Water Framework Directive (Directive 2000/60/EC), the Habitat and Birds Directives (Council Directive 92/43/EEC and Directive 2009/147/EC) or the Floods Directive (Directive 2007/60/EC) foster the restoration of river and floodplain ecosystems [22]. The decade of 2021–2030 is also assigned as the United Nations decade on ecosystem restoration. It emphasizes that nowadays there is still an urgent need to restore degraded ecosystems (https://www.decadeonrestoration.org/).

Restoration activities in floodplains and riparian zones, however, can also affect soils in these areas through the use of heavy machinery, resulting in soil compaction, or the disturbance and mixing of the soil [23–25]. These negative effects and disturbances can persist, at least for a decade [23,25]. Soil development is, compared to the changes in vegetation or hydrology, a slow process [26,27] which explains why soils would not recover within a relatively shorter period after the restoration impact [25]. The assessment of the positive or negative impacts of restoration on riparian and floodplain soils, is of major importance [28] as crucial ecosystem services and functions are associated with soils in this zone [29].

The aim of this review is therefore to assess if and how riparian soils and soil properties are addressed in the research on floodplain and river restoration and in the research on floodplains and riparian zones with direct implications to future restoration projects.

The objectives of this review are:
1. To give an overview on research in floodplains and riparian zones of the world with implication to restoration projects in the last 20 years;
2. To assess in which kind and to what extent soils are addressed in the research;
3. To recommend further research needs on soil protection in floodplains.

2. Materials and Methods

This literature review is based on the principles of Pickering and Byrne [30] and the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [31]. In July 2020 a literature research was performed in Scopus and Web of Science. As the search for the terms “soil protection” in combination with “floodplain restoration” or “river restoration” resulted in only 12 or 10 articles, respectively, a broader understanding of soil protection had to be applied. In a first search article titles, keywords, and abstracts were searched for the terms soil, protection, river or floodplain, restoration, or construction and additionally water framework directive or WFD. A second search in the same databases in article titles, keywords, and abstracts with the terms soil, restoration, and riparian zone was performed. The review should cover all aspects of soil protection in floodplains and
After duplicates were removed the search returned 1038 records. These articles were screened by abstract and 860 were excluded. Only journal articles were included. Books and conference proceedings were excluded from the beginning. Articles were excluded if the study area was different from rivers, streams, floodplains, or riverine/riparian wetlands. Water reservoirs, wetlands with no further specification (e.g., as riparian wetland) and artificial wetlands (e.g., treatment wetlands), coastal areas (like mangroves), and lakes were not considered for this review. Articles only concerning other topics like vegetation or forest growth, seedbanks, fish productivity, the functioning of a special geomaterial or geosynthetic, a construction work in a place different than a floodplain or river, landfills, etc., and no direct link to soil and soil protection were also excluded. The spatial scale was set to the floodplain or riparian zone. No restrictions were made to the geographic or climatic region. Articles at the spatial scale of river basins or watersheds and no direct reference to the soils in the riparian zone were also excluded. Only research articles fully written in English were considered for this review. This resulted in 178 full-text articles which were assessed for eligibility. Another 78 articles did not meet the criteria mentioned above. Finally, 100 full-text articles were included in the qualitative analysis.

The 100 articles were scanned for study region, year, and available soil information in the research. The soil information was grouped into categories including soil properties (physical, chemical, and biological), detailed soil classification, other type
of classification like alluvial soils, and other soil information like the use of soil maps (Appendix A Table A1).

3. Results

3.1. Overview on Research in Floodplains and Riparian Zones of the World

Research on soil protection was conducted on every continent or geographic region, respectively, with the exception of Antarctica (Table 1). Most research (44 published articles) focusses on soil protection in floodplains and riparian zones in North America. In second place, 25 articles have been published about study sites in Europe. In one article research was conducted in Europe and North America. Then, 12 articles focused on research in Asia, 12 in Oceania, four in South America, and one in Africa. In three articles the geographic region was not specified, for example when research focused on models or frameworks without the need of a special study area.

Table 1. Number of articles on soil protection in floodplains or riparian zones per geographic region.

| Region       | Africa | Asia | Europe | North America | South America | Oceania | Not Specified | Total |
|--------------|--------|------|--------|---------------|---------------|---------|---------------|-------|
|   1          | 12     | 25   | 44     | 4             |               | 12      | 3             | 100   |

1 One article covered study sites in Europe and North America. 2 Oceania here only comprises Australia and New Zealand. For a detailed classification of the continents c.f. the United Nations definitions on geographic regions (https://unstats.un.org/unsd/methodology/m49/).

In total, research was conducted in over 24 different countries; half of them are in Europe. In most countries less than four studies have been realized. Most studies were carried out in the USA, followed by Australia with 11 studies and China with eight. Five studies were realized in Switzerland (Table 2). One article did not restrict the research to a specific country but focused on the whole Alpine area [32]. Studies in the USA were conducted in 22 different states.

Table 2. Number of study sites per country. Only countries with more than four studies are considered in this table.

| Country   | USA | Australia | China | Switzerland |
|-----------|-----|-----------|-------|-------------|
|           | 41  | 11        | 8     | 5           |

Regarding the climate zones after Schultz [33] approximately 50% of the articles covered study sites in the midlatitudes. Over 40% were carried out in the subtropics and dry tropics. In the boreal zone 2% of the studies were realized. In the humid tropics 3% of the studies were realized. In 2% of the studies no climate region could be assigned.

The number of articles published per year between 2000 and 2020 shows that only about one-third (33 articles) of the 100 articles has been published in the first decade between 2000 and 2010 (Figure 2). More than two-thirds of the considered papers have been published in the second decade between 2010 and July 2020 (67 articles), indicating an increasing interest in this topic. Most papers were published in 2017 and 2019 with 10 and nine papers each year.
Methods used over the period considered did not change significantly over time. Most research was done by field work (approx. 74%), e.g., soil surveys, field mapping, field experiments, and sampling. Laboratory experiments were carried out in about 10% of the studies. About 16% used models for the research, e.g., GIS-based models. Most studies included statistical analysis. Some studies used combined methods, e.g., field work and modeling.

3.2. Soil Information in the Articles on Soil Properties

Soil information in the articles was divided into physical, chemical, and biological soil properties, soil classification, and other soil information (Table 3). Soil information is vastly used in the examined research articles. Only three articles did not mention any soil information. In the remaining articles soil information is used to a different extent. A detailed table with the parameters of each soil information category is provided in the Appendix A (Table A1).

Table 3. Number of articles per soil information category (chemical, physical, biological properties, soil classification, other soil information, and no soil information).

| Physical Properties | Chemical Properties | Biological Properties | Detailed Classification | Other Soil Classification | Other Soil Information | No Soil Information |
|---------------------|---------------------|-----------------------|-------------------------|--------------------------|-----------------------|---------------------|
| 76                  | 56                  | 21                    | 32                      | 6                        | 9                     | 3                   |

In 76 articles some kind of physical soil parameters were used either to describe the study region or were investigated during the study. Physical soil parameters described by the different authors mainly contained classical soil physical parameters like texture and other descriptions of particle sizes and particle contents (e.g., fine material or coarse elements), electrical conductivity, porosity, soil temperature, or (dry) bulk density. In many cases soil parameters concerning the water household of soils like soil moisture content, (saturated) hydraulic conductivity, water holding capacity, infiltration, permeability, or field capacity are used, too. Some authors described more general parameters like the drainage situation or hydric conditions of the sites, but did not go into more detail. Other physical parameters mentioned were the pore-water pressure, the Atterberg limits, the specific gravity of the soil, (effective) cohesion, soil erodibility or an erosion coefficient, shear strength or shear stress, the (internal) friction angle, the van Genuchten parameters, and the rooting zone.

Chemical soil parameters were mentioned in 56 articles. Soil chemical parameters can be divided into several categories. In many articles nutrients were assessed, with focus on inorganic nitrogen (N) forms (NO$_3^-$, NO$_2^-$, NH$_4^+$, N$_2$O, total N), different phosphorus (P) speciations (e.g., plant available P, soluble reactive P, total P) and potassium (K) (e.g.,
Despite being nutrients, especially nitrogen and phosphorus are seen as non-point source pollutants, too. Other contaminants investigated are (heavy) metals like Cd, Pb, Hg, Zn, Cr, Cu, and others. In one paper organo-chlorine pesticides were examined. Another important soil chemistry category is soil organic matter (SOM). Here, different forms and types of SOM were addressed, like total carbon, inorganic and organic carbon, recalcitrant organic carbon (ROC), refractory index for carbon (RIC), or coarse particular organic matter (CPOM). Other parameters assessed were pH, salinity, CaCO$_3$, C/N, and isotopic ratios of C and N. One article mentioned the fertility of the soils investigated, but did not go further into detail.

Soil biological parameters were considered in 21 articles, containing data on soil organisms and processes driven by these inhabitants. In the research, soil invertebrates, soil microbial community structure (e.g., denitrifier and ammonium oxidizer density), and microbial number, species traits, operational taxonomic units and phylogenetic diversity, soil enzyme activity, denitrification enzyme activity (DEA), and actual denitrification were addressed. Other parameters were net potential nitrification, net potential N mineralization, potential mineralizable N, potential denitrification (rate), potential C mineralization, and microbial biomass C. Besides soil invertebrates and microorganisms, also root parameters, like root density, total belowground plant biomass, and root exudates, were examined. One article mentioned general biological activity features, but did not provide more details.

Some kind of soil classification/taxonomy is mentioned in 38 articles, whereas it has to be differentiated between a detailed classification from a common classification system or another soil description. Detailed soil description is provided in roughly one-third of the considered articles for this review (32 articles) and comprises descriptions on soil series, soil associations, soil types, soil map units, or soil orders based on the US Soil Taxonomy, the WRB, the Australian classification system, the French classification system, and others. In most articles these parameters are mentioned in detail (Which soil types? Which soil series?), but in few articles it is only mentioned that soil map units for example are used, but not which ones. In the remaining six articles soils are described more in general, for example as alluvial or hydric soils, but do not classify the soils in a common pedological classification system.

In the 32 articles that provide a detailed soil classification it is interesting in which combination and to which extent soil classification is combined with soil physical, chemical, and biological parameters (Table 4).

**Table 4.** Combination of physical, chemical, and biological soil properties in the 32 articles that provide a detailed soil classification [number of articles]. Articles that provide other soil information were not considered.

| Physical + Chemical + Biological Properties + Classification | Physical + Chemical Properties + Classification | Physical Properties + Classification | Chemical Properties + Classification | Biological Properties + Classification | Classification Only |
|--------------------------------------------------------------|-------------------------------------------------|-----------------------------------|-------------------------------------|--------------------------------------|---------------------|
| Physical + Chemical + Biological Properties + Classification | 6                                              | 12                                | 5                                  | 3                                    | 0                   | 6                   |

Only six articles consider physical, chemical, and biological soil properties in combination with a detailed soil classification. Approximately one-third (12 articles) additionally mention soil physical and chemical parameters in their research. Five articles provide physical soil properties and three articles chemical soil properties in a combination with a detailed soil classification. Additional soil biological properties without chemical or physical properties were not covered in the research. Six articles provided a detailed soil classification only.

Good examples of the provision and use of soil information are mostly those articles that explicitly address soil properties in their research. For example, to describe the morphology of riparian soils in a restored floodplain in Switzerland as a restoration monitoring measure, Fournier et al. [34] provide not only detailed soil taxonomy, but also
basic soil physical (texture, coarse soil), soil chemical (organic matter content and type, hydromorphological features), and soil biological parameters (root density and general biological activity features). In a comparison of the effects of different stream restoration practices (designed channel restoration vs. ecological buffer restoration) on riparian soils, beside USDA soil map units, the soil organic matter content, bulk density, soil moisture, texture, and root biomass were used and compared [25]. Other examples are the studies of Kauffman et al. [35], Clement et al. [36], Smith et al. [37], and Sutton-Grier et al. [38] which all provide soil information from all categories in their research.

In the 68 articles that do not provide a detailed soil description from a common soil classification, 11 articles, however, provide information on soil physical, soil chemical, and soil biological properties (Table 5).

Table 5. Combination of physical, chemical, and biological soil properties in the 68 articles that do not provide a detailed soil classification [number of articles].

| Physical + Chemical + Biological Properties | Physical + Chemical Properties | Physical + Biological Properties | Chemical + Biological Properties Only | Biological Properties Only | Chemical Properties Only | Physical Properties Only |
|--------------------------------------------|--------------------------------|----------------------------------|--------------------------------------|---------------------------|------------------------|-------------------------|
| 11                                         | 16                             | 3                                | 1                                    | 0                         | 7                      | 24                      |

15 out of the 24 covered engineering topics.

In 16 articles a combination of soil physical and soil chemical parameters is used. Soil physical parameters in combination with soil biological parameters were covered in three articles. Soil chemical parameters and soil biological parameters have been combined in one article only. If only one soil property was investigated or mentioned, most articles (24) provided information on soil physical parameters only, seven on soil chemical parameters only. Only soil biological parameters were used in none of the reviewed articles. Fifteen out of the 24 articles which provide soil physical parameters covered engineering topics only.

Soil information that could not be classified into the before mentioned categories is used in nine articles. These data comprise information on the use of soil maps or soil databases for example, the number and lower boundary of the soil layers or information on soil morphology (soil typicality, dynamism, and diversity). In some cases, soil properties that are taken from the maps or databases are further specified, but in other articles there is no further information on the kind of soil properties (chemical, physical, biological) or soil taxonomy.

3.3. Information on Soils in Articles in Connection with Engineering and Land Management

In total, 18 articles covered engineering topics, like soil bioengineering, river bank stability, or erosion control which can also be understood as some kind of soil protection. In these articles physical soil properties are considered only, e.g., shear strength, cohesion, texture or hydraulic conductivity. In the engineering articles neither soil chemical properties nor soil biological properties were used. None of the articles provided a detailed soil classification. One article considers additional soil biological properties (root system and root biomass) [39].

Another 32 articles deal with land management and land use, restoration planning, and the evaluation of restoration efficiency. In this category no clear pattern of the use of soil information is observable. Chemical and physical soil properties are described in the same extent in the articles as detailed soil classification (16, 24 and 16 articles, respectively). Soil biological properties play a minor role and are mentioned in six articles only. The provision of soil data differs between the 32 articles as few articles provide chemical, physical, biological soil properties in combination with a detailed soil classification (three articles), most do mention only parts of the different soil data types in a variable proportion.
4. Research Needs on Soil Protection in Floodplains

The results in Section 3.1 show that research on floodplains and riparian zones is not evenly distributed worldwide. Most research in the regarded period was conducted in North America and Europe, providing a broad base of knowledge on restoration of floodplains and the riparian zones in these areas. Other regions like Oceania, South America, Asia, and Africa are underrepresented in the research which leads to a lack of knowledge not only on restoration in riparian zones and floodplains, but also on soil information in these regions. More research in these regions of the world is highly recommended. When regarding the countries in which research on the individual continents is conducted it becomes clear that research mostly concentrates on single countries like the USA, Australia, Brazil, and China. The number of articles published on floodplain and riparian zone research was not distributed evenly over the two decades considered in this review. With two-thirds of the articles published in the second half of the reviewed period this shows the increasing concern and importance of research in the floodplains and riparian zones.

To protect soils and to interpret results of the research in the soil context it is important to know detailed properties of the regarded soils. Soil properties are described in most reviewed articles, but the extent of the provision and description of the soil properties varies considerably. Soil properties are important indicators when evaluating the soil quality and assessing soil functions [40]. Basically, soil quality is the capacity of a soil to function [41]. Soil quality depends on soil inherent and dynamic properties. Inherent properties are mostly influenced by the soil-forming factors (e.g., parent material, topography, time). Dynamic properties are influenced by human management and natural disturbances (e.g., land use or the construction of buildings or roads). Typical inherent soil properties are the soil texture or the drainage class. Management-dependent soil properties comprise among others the organic matter content, infiltration, biological activity, or soil fertility. The different soil properties can interact and limit other soil properties. Finally, the dynamic soil properties provide information about the ability of a soil to provide ecological functions and services [40]. Indicators for soil quality are traditionally divided into soil physical, soil chemical, and soil biological parameters [40,42]. In the reviewed articles over 75% provide information on soil physical parameters and hence information on the soil hydrologic status, on the availability of nutrients, on aeration, limitations on root growth, or the ability to withstand physical disturbances [40,42]. This information on soil physical parameters is very important for soil protection. Although not every article contains the same physical parameters, basic information on texture or particle sizes and soil moisture are given in most articles. Chemical parameters, mentioned in over 50% of the reviewed articles, are important to evaluate nutrient availability, water quality, buffer capacity, or the mobility of contaminants. Soil biological parameters, like abundance and biomass of soil organisms and their byproducts can also serve as an indicator for a functioning soil [42]. Biological soil parameters are assessed only in about 20% of the articles. It can be summarized that in current research in floodplain and riparian zones soil physical properties, chemical properties, and biological properties are used. There is a lack of information, especially on soil chemical and soil biological parameters. Both parameters can provide important insights in soil functioning and the reaction of the soils to certain conditions.

A detailed description from a common soil classification system like the WRB, the US soil taxonomy or a national classification system can be very informative not only for soil scientists. Soil classification systems are based on soil properties that are defined in diagnostic horizons, properties, and materials [15]. Therefore, when providing a detailed soil description from a common soil classification system, a lot of information on soil physical, soil chemical, and soil biological properties can be derived from using this classification. This information is missing, however, in about two-thirds of the reviewed literature. In these articles that do not provide a detailed soil description from a common soil classification system the majority of the authors though provide additional information on physical, chemical, and biological soil properties or combinations of these properties. The group of the articles with only physical soil data described mostly comprises articles...
dealing with engineering topics. In this group, except for one article that mentions some soil biological characteristics [39], soil is characterized by the physical characteristics only while other parameters like chemical or biological parameters are not considered. In this field, soil seems to be a granular medium only, serving as a building material, not as an important ecosystem compartment. But even if the physical and geotechnical properties of soils are most important for engineering purposes, a pedological view of soils, integrating some basic information on soil classification, on chemical and biological properties, might be valuable for engineers, too. As engineering measures usually comprise the use of (heavy) machinery, these measures can also be considered as a kind of construction work. This usually implies that the floodplain and riparian soils, adjacent to the riverbank or engineering site, are affected by these measures, too. Therefore, at least a minimum dataset on the soils of the whole site should be considered in projects, working in floodplains and riparian zones.

Other, more general, soil descriptions like the term “alluvial soils” for example, can give only general information on the soil development and on-site characteristics, but do not provide detailed information on the soil properties. As the physical, morphological, chemical, and mineralogical properties of these soils are strongly influenced by the alluvial parent material coming from the river, the soil characteristics, e.g., the soil texture and the related properties, can vary considerably [13]. In contrast, when a soil is classified within a common classification system, for example as a Gleysol (WRB), it is obvious that this soil must be saturated with groundwater long enough to develop these gleyic properties [15]. In the WRB, additional information on the soils and their properties can be deduced from the principal and supplementary qualifiers, such as the presence of an organic surface layer (qualifier: histic) or non-cemented secondary carbonates accumulated (qualifier: calcare). Information on organic horizons or layers or waterlogging conditions due to high groundwater tables in floodplains and riparian zones are very valuable as especially these soils are highly susceptible to compaction for example [43]. So even if there is no additional information on physical, chemical, or biological soil properties, from a detailed soil description many soil characteristics can be deduced.

If a detailed investigation and description of the soils and their characteristics of the study sites is not possible there are other opportunities that should be considered to assess at least basic soil information of the site. For most regions of the world free soil information is available online from different organizations. A compendium of available data worldwide and for specific regions has been provided by ISRIC, the International Soil Reference and Information Centre for example [44]. They also maintain other useful sites and services like the World Soil Information Service (WoSIS) [45] and the SoilGrids platform [46] which can be helpful to consider.

As the results show, soil information is available in the large majority of the research papers, but it becomes also clear that in most cases soil information is incomplete or very specific only. To protect soils in floodplains and riparian zones, especially in the context of restoration works, a more pedological view of soils is necessary. This would not only be important for restoration projects directly, but also for all research in floodplains and riparian zones with the objective to contribute to restoration projects, for example in the prioritization of restoration areas.

Restoration projects impact soils in floodplains and riparian zones [25] and can therefore often be regarded as construction works. In recent years, soil protection on construction sites has become more and more important, for example in Switzerland or Germany. Known as “Bodenkundliche Baubegleitung” in the German-speaking area, it aims to protect soils from physical disturbance and contamination prior to and during construction. This means that after finishing the construction, the soil should be able to fulfil its natural functions again [47,48]. Detrimental soil changes that can occur on construction sites comprise soil compaction, erosion and discharge of substances, contamination, mixing of different soil substrates, and mixing of natural soil substrate with technogenic materials [48]. The soil protection on construction sites concept has not been developed for restoration projects,
but as many restoration projects are comparable to construction sites, this concept is also applicable to restoration projects.

Soil protection on construction sites is not only applied during the construction works, but also prior to the construction in the planning process and is also involved post-construction in the monitoring and documentation of the project [47,48]. The lack of sound knowledge about soils has been identified as one of the factors hampering effective ecological restoration [49]. In the soil protection on construction sites concept various soil information is assessed for planning the construction work and appropriate soil protection measures during construction. This soil information comprises information on the soil types and their special characteristics (e.g., susceptibility to compaction or organic soils), coarse fragments, texture and structure of the soil, bulk density, pH, soil organic matter content, water content, rooting depth, and calcium carbonate content [47,48]. This soil information could be applied as a minimum dataset on soils in all research in floodplains and riparian zones and in restoration projects. Additionally, the nutrient and/or pollution status of the soil might be a useful parameter to be considered. The parameters proposed for the minimum soil data set contain stable and dynamic parameters. For dynamic parameters a continuous monitoring program might be useful. If not, many dynamic parameters like the physiological rooting depth for example can be deduced from easy to assess parameters like soil depth and soil texture. Also in the USDA stream restoration handbook [50] it is recommended to obtain background information on the sites, i.e., about soils. In general, to avoid detrimental soil changes many parts of the soil protection on construction sites concept could be easily integrated in the protocols for river, floodplain or riparian buffer restoration projects, as well as in soil bioengineering practices. In soil bioengineering practices there is great potential to integrate this minimum soil data set and soil protection measures during construction. Rey et al. [51] highlight the importance of the incorporation of current findings of the research in geosciences, for example soil science, in soil bioengineering practices. Further, scientist and practitioners should cooperate and exchange current issues and knowledge.

5. Conclusions

1. Research on floodplains and riparian zones of the world is not distributed evenly over the different continents, with the majority of research in this area conducted in North America, especially in the USA. The research on floodplains and riparian zones is also not distributed evenly over the time covered in this review with two-thirds of the research published in the second decade between 2010 and 2020.

2. Soils are somehow addressed in most articles, but the kind and extent of provided soil information varies significantly between the articles. Mostly physical soil information is provided, followed by chemical soil information. Only one-fifth provides soil biological information. One-third provides a detailed soil description from a common classification system. Soil information in the field of engineering is limited to physical data only.

3. Soils are addressed in the majority of the research, but soil information is often incomplete from a soil scientists’ view. It is recommended to integrate at least a minimum data set on soil information in all research conducted in floodplains and riparian zones. This minimum data set comprises soil data used in the soil protection on construction sites concept: soil types and associated special characteristics (e.g., susceptibility to compaction), coarse fragments, texture and structure of the soil, bulk density, pH, soil organic matter content, water content, rooting depth, and calcium carbonate content. Additionally, the nutrient and/or pollution status might be a useful parameter. Further, at least the use of regional soil databases can give important information on the soils in the study area, if field work is not possible.

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**Abbreviations**

- As: Arsenic
- ASC: Australian Soil Classification System
- C: Carbon
- CaCO$_3$: Calcium carbonate
- Cd: Cadmium
- C/N: Carbon/nitrogen ratio
- CPOM: Coarse particular organic matter
- Cr: Chromium
- Cu: Copper
- DEA: Denitrification enzyme activity
- DOC: Dissolved organic carbon
- DOM: Dissolved organic matter
- DON: Dissolved organic nitrogen
- EC: Electrical conductivity
- Fe: Iron
- Hg: Mercury
- IC: Inorganic carbon
- K: Potassium
- N: Nitrogen
- Ni: Nickel
- NO$_3^-$: Nitrate
- NO$_3^-$-N: Nitrate nitrogen
- NO$_2^-$: Nitrite
- NH$_4^+$: Ammonium
- NH$_4^+$-N: Ammonia nitrogen
- N$_2$O: Nitrous oxide
- NO: Nitric oxide
- NZG: New Zealand Soil Classification
- OC: Organic carbon
- OM: Organic matter
- P: Phosphorus
- PB: Lead
- PO$_4^{3-}$: Phosphate
- RIC: Refractory index for carbon
- ROC: Recalcitrant organic carbon
- RO: Référentiel Pédologique (French Soil Classification)
| Character | Description |
|-----------|-------------|
| S         | Sulfur      |
| Sb        | Antimony    |
| SiBCS     | Sistema Brasileiro de Classificação de Solos (=Brazilian Soil Classification System) |
| Sn        | Tin         |
| SOC       | Soil organic carbon |
| SOM       | Soil organic matter |
| SRP       | Soluble reactive P |
| TC        | Total carbon |
| TDC       | Total dissolved carbon |
| TDN       | Total dissolved nitrogen |
| TBGB      | Total belowground biomass |
| TK        | Total potassium |
| TN        | Total nitrogen |
| TOC       | Total organic carbon |
| TP        | Total phosphorus |
| V         | Vanadium    |
| WRB       | World Reference Base for Soil Resources |
| Zn        | Zinc        |
### Appendix A

**Table A1.** Articles selected for this review, continent, country, and soil information categories.

| Source                        | Article Reference | Continent | Country | Category | Chemical Properties | Physical Properties | Biological Properties | Detailed Classification | Other Classification | Other Soil Data |
|-------------------------------|-------------------|-----------|---------|----------|---------------------|----------------------|------------------------|-----------------------|--------------------|-----------------|
| Agouridis et al. 2005         | [52]              | North America | USA, Kentucky | Management | -                  | -                    | -                      | Hagenstown (Fine, mixed, mesic Typic Hapludalf); McAlpin (Fine, mixed, mesic Mollic Hapludalf); Woodcup (Fine, mixed, mesic Typic Argiudoll) | -                  | -                |
| Arneklev & del Valle de Lersundi 2008 | [63]          | Europe     | Spain    | Management | OM, CaCO₃, salinity | Texture, moisture, temperature, EC | -                      | Loamy-skeletal, mixed, mesic, Aridic Ustorthent; Coarse-loamy, mixed, mesic, Aridic Ustifluvent; Fine-silty, mixed, mesic, Aridic Ustorthents; Entisols | -                  | -                |
| Andrews et al. 2011           | [54]              | North America | USA, Kentucky | Other Fertility | Permeability, water holding capacity, rooting zone | -                  | -                      | Fine-loamy, mixed, mesic Dystric Fluvic Eutrochrepts (USDA 1996) | -                  | -                |
| Arentind et al. 2012          | [65]              | Europe     | UK       | Engineering | -                  | Cohesion, texture | -                      | -                     | -                  | -                |
| Atkinson & Lake 2020          | [66]              | North America | USA, Texas | Management | -                  | -                      | -                      | -                     | -                  | -                |
| Bariteau et al. 2013          | [67]              | North America | Canada | Engineering | -                  | Texture | -                      | -                     | -                  | -                |
| Beauchamp et al. 2015         | [68]              | North America | USA, Maryland | Management | OM, pH, C/N, plant available macronutrients and micronutrients | Texture | -                      | -                     | -                  | -                |
| Bedinon et al. 2013           | [69]              | North America | USA, New Jersey | Other | Mottling | Texture, drainage | -                      | Mtn Entisols; Histic soils; Histosols | -                  | -                |
| Bissels et al. 2004           | [70]              | Europe     | Germany  | Management | Plant available P and K, TN, TC, CaCO₃, OM, C/N | Texture | -                      | -                     | -                  | Alluvial soils |
| Botero-Acosta et al. 2017     | [71]              | North America | USA, Oklahoma | Engineering | -                  | Water content, field capacity, wilting point, saturated hydraulic conductivity | -                      | -                     | -                  | STASGSO soil map (soil types), Soil Characterization Database (physical soil properties) |
| Brovelli et al. 2012          | [72]              | n.a.       | n.a.     | Other | Various (not further specified) | Various (not further specified) | Various (not further specified) | -                     | -                  | -                |
| Buchanan et al. 2012          | [73]              | North America | USA, New York | Management | -                  | Erodibility, texture | -                      | -                     | -                  | -                |
| Burger et al. 2010            | [74]              | Oceania    | Australia | Management | NO₃⁻, NO₂⁻, NH₄⁺, plant available P, EC, pH, TC, TN | -                      | -                      | Grey, Yellow, and Brown Sodosols and Chromosols (ASC 1996) | -                  | -                |
| Bushugyan et al. 2016         | [75]              | Asia       | Ukraine  | Other | SOC, pH, TN | Bulk density | -                      | -                     | -                  | -                |
| Cabezas & Corin 2010          | [76]              | Europe     | Spain    | Other | TOC, TN, C/N, RC, ROC | Bulk density | -                      | -                     | -                  | -                |
| Clementi et al. 2015          | [77]              | Europe     | France   | Other | Hydromorphological features, OM, pH | Texture, bulk density | Denitrification activity, roots | Fine silty-clay loam, mixed, mesic Typic Hapludoll (USDA 1990) | -                  | -                |
| Source | #Article | Continent | Country | Category | Chemical Properties | Physical Properties | Biological Properties | Detailed Classification | Other Classification | Other Soil Data |
|--------|----------|-----------|---------|----------|---------------------|---------------------|-----------------------|------------------------|--------------------|-----------------|
| Das 2016 | [67] | Asia | India | Engineering | - | Shear strength, dry density, Atterberg limits, specific gravity, texture | - | - | - | - |
| Davis et al. 2006 | [68] | North America | USA, Nebraska | Other | OM, TN, TK, TP, pH | Temperature, moisture, texture | Soil invertebrates | - | - | Groundwater level |
| De Mello et al. 2017 | [69] | South America | Brazil | Management | - | Bulk density, available water capacity, saturated hydraulic conductivity | - | - | - | Number of layers, lower boundary of layers |
| Del Tánago & de Jalón 2000 | [70] | n.a. | n.a. | Management | - | Permeability | - | - | - | - |
| Dhanu et al. 2016 | [71] | Europe | Belgium | Other | OC, TN, EC, pH, N2O fluxes | Texture | DEA | - | - | - |
| Dietrich et al. 2014 | [72] | Europe | Sweden | Management | OM, mass fraction of C and N, isotope ratios (\(\Delta^{13}C\); \(\Delta^{15}N\)), TC = TOC | Texture, water holding capacity | - | - | - | - |
| Duong et al. 2014 | [73] | Asia | Vietnam | Engineering | - | Water content, bulk density, saturated shear strength, saturated hydraulic conductivity, dry density, main grain size, effective cohesion, texture | - | - | - | - |
| Duti et al. 2020 | [74] | Europe | Netherlands | Engineering | - | Internal friction angle, cohesion, texture, shear stress | - | - | - | - |
| Dybala et al. 2019 | [75] | North America | USA, California | Other | TC, carbon stock | Bulk density | Cenozoic (Fine, mixed, active, temolic, Aquic Xerofluvents) | - | - | - |
| Fernandes et al. 2020 | [76] | Europe | Portugal | Engineering | - | Cohesion | - | - | - | - |
| Fourrier et al. 2015 | [77] | Europe | Switzerland | Other | - | Hydraulic conditions | Sparsic leachate | - | - | - |
| Fourrier et al. 2013 | [78] | Europe | Switzerland | Other | OM, OM-type, hydromorphological features | Texture, coarse elements | Root density, biological activity features | RP (2006) (WRB 2006): REDUCISOLS fluvio-carbonátiques (Gleyic Fluvisols (Calcrite)); FLUVIOPLEDS alcalines (Fluvic Calcaric); REDUCISOLS typiques carbonatés (Fluviandic Calcaric) | - | Soil morphology: soil diversity, soil dynamism, soil typicity |
| Franklin et al. 2020 | [79] | Oceania | Australia | Other | TN, TC, NH4+, NO3−, NH4+, pH, EC, (DOC, DON, DOK, C/N, TK, TKN, inorganic N in leachate) | Texture, moisture | Hard pedal mottled-yellow-grey duplex soil (Atlas of Australian Soils 1960-1968); USDA (2014): Paleustalf | - | - | - |
| Gageler et al. 2014 | [80] | Oceania | Australia | Management | TN, SOC, NO3−, NH4+ | Texture, infiltrability, bulk density | Red Foremull, Clay loamy (ASC 1996); WRB (2014): Nitosols | - | - | - |
| Garvin et al. 2017 | [81] | North America | USA, Oklahoma | Other | Cd, Pb, Zn | - | - | - | - | - |
| Source                        | Article            | Continent | Country                  | Category | Chemical Properties | Physical Properties | Biological Properties | Detailed Classification | Other Classification | Other Soil Data |
|------------------------------|-------------------|-----------|--------------------------|----------|---------------------|---------------------|----------------------|------------------------|----------------------|------------------|
| Giese et al. 2000            | [80]              | North America | USA, South Carolina      | Other    | SOC                 | -                   | -                    | Tytic Endoaquents;     | -                    | -                |
|                              |                   |           |                          |          |                     |                     |                      | Tyritic Fluvaquents;   |                      |                  |
|                              |                   |           |                          |          |                     |                     |                      | Gleysallic-Hydromorphic|                      |                  |
|                              |                   |           |                          |          |                     |                     |                      | Fluvaquents;           |                      |                  |
|                              |                   |           |                          |          |                     |                     |                      | Grossarenic Hapludults;|                      |                  |
|                              |                   |           |                          |          |                     |                     |                      | Arenic Endoaquults    |                      |                  |
| Gift et al. 2010             | [3]               | North America | USA, Maryland            | Other    | OM, N2O             | Moisture            | DEA, root biomass    | -                      | -                    | -                |
| Gold et al. 2001             | [31]              | North America | USA, various             | Other    | hydro- morphological | Soil wetness        | -                    | Hydric soils           | -                    |                  |
| Giusso & Bizzoni 2017        | [82]              | Europe     | Italy                    | Management | Moderately calcareous | Water content,    | -                    | -                      | -                    |                  |
| Gao et al. 2018              | [40]              | Asia       | China                    | Other    | Organic-chlorine     | Texture             | Soil microbial        | Brown soil             | -                    |                  |
|                              |                   |            |                          |          | pesticides          |                     | community structure  | -                      |                      |                  |
| Hale et al. 2018             | [44]              | Oceania    | Australia                | Management | TC, TN, C/N, plant | Water content, bulk | -                    | Various soil types (ASC 1996) | -                    | -                |
|                              |                   |            |                          |          | available P, C/OM    | density, texture    |                      | -                      |                      |                  |
| Hale et al. 2014             | [45]              | Oceania    | Australia                | Management | EC, pH, mg/mg N, | -                   | -                    | -                      | -                    | -                |
|                              |                   |            |                          |          | NO3−, NO2−, NH4+   |                     |                      | -                      |                      |                  |
| Hasselquist et al. 2017      | [87]              | Europe     | Sweden                   | Other    | ∆15N, bulk C and N, | Texture             | -                    | -                      | -                    |                  |
| Higgerson et al. 2019        | [46]              | Oceania    | Australia                | Management | -                   | Particle size       | -                    | -                      | -                    |                  |
| Jersch & Robertson 2001      | [47]              | Oceania    | Australia                | Management | -                   | Bank stability, soil| -                    | -                      | -                    |                  |
| Janzen et al. 2019           | [48]              | Europe     | France, Switzerland      | Engineering | -                   | -                    | -                    | -                      | -                    |                  |
| Jurasak & Drake 2016         | [49]              | North America | USA, Kansas             | Other    | Pb, Zn              | Particle size       | -                    | -                      | -                    |                  |
| Kaulfman et al. 2004         | [50]              | North America | USA, Oregon             | Management | SOM, mineral N       | Textures, bulk density, | TBCB, net potential  | -                      | -                    |                  |
|                              |                   |            |                          |          | (NO3−, NO2−, NH4+ + N) | porosity, irrigation, | nitritation, net potential | -                      |                      |                    |
|                              |                   |            |                          |          |                     | moisture            | N-mineralization     | N-mineralization        |                      |                  |
| Kores et al. 2019            | [51]              | North America | USA, various            | Management | pH, OM, NO3−, NH4+  | Bulk density, moisture | Denitrification potential, | -                      | -                    |                  |
|                              |                   |            |                          |          |                    |                     | DEA, potential C     | -                      |                      |                    |
|                              |                   |            |                          |          |                     |                     | mineralization       | -                      |                      |                    |
| Langford et al. 2009         | [52]              | North America | USA, Mississippi        | Engineering | -                   | -                    | -                    | -                      | -                    |                  |
|                              |                   |            |                          |          |                     |                      |                      | Zekiah (Course-loamy, silt-loamy, active, acid, more Type Fluvaquents); |                      |                  |
|                              |                   |            |                          |          |                     |                      |                      | Issaquah (course-loamy, mixed, active, more Fluvaquentic Dystrudepts); |                      |                  |
|                              |                   |            |                          |          |                     |                      |                      | Flatbush (fine-loamy, mixed, active, nonacid, more Fluvaquentic |                      |                  |
|                              |                   |            |                          |          |                     |                      |                      | Endoaquents);        |                      |                  |
|                              |                   |            |                          |          |                     |                      |                      | Widewater (fine-loamy, mixed, active, acid, more Fluvaquentic |                      |                  |
|                              |                   |            |                          |          |                     |                      |                      | Codorus (fine-loamy, mixed, active, more Fluvaquentic |                      |                  |
|                              |                   |            |                          |          |                     |                      |                      | Dystrudepts);        |                      |                  |
|                              |                   |            |                          |          |                     |                      |                      | Limbside (fine-silty, mixed, active, more Fluvaquentic |                      |                  |
|                              |                   |            |                          |          |                     |                      |                      | Inceptisols)           |                      |                  |
| Taun & Ceco 2002             | [53]              | North America | USA, California         | Engineering | -                   | Bank cohesion, texture | -                    | -                      | -                    |                  |
| Taub et al. 2013             | [54]              | North America | USA, Maryland            | Management | SOM                 | Bulk density, moisture, | Root biomass           | -                      | -                    |                  |
|                              |                   |            |                          |          |                     | texture             |                      | -                      |                      |                  |
Table A1. Cont.

| Source                        | #Article | Continent | Country          | Category  | Chemical Properties          | Physical Properties          | Biological Properties | Detailed Classification | Other Classification | Other Soil Data |
|-------------------------------|----------|-----------|------------------|-----------|-------------------------------|-----------------------------|----------------------|------------------------|----------------------|-----------------|
| Lee et al. 2011               | [95]     | Asia      | South Korea      | Other     | -                             | -                           | -                    | -                      | -                    | Soil information (= soil properties, not further specified) from soil maps is used in model |
| Li et al. 2006                | [96]     | Asia      | China            | Engineering | -                             | Moisture, shear stress      | -                    | -                      | -                    |                |
| Landwehr et al. 2000          | [97]     | n.a.      | n.a.             | Engineering | -                             | Texture, hydraulic conductivity, van Genuchten parameters, effective cohesion, internal friction angle, residual and saturated water content | -                    | -                      | -                    |                |
| Madina & Stulli 2020          | [98]     | South America | Brazil          | Engineering | -                             | -                           | -                    | -                      | -                    |                |
| Maestro et al. 2017           | [99]     | Europe    | Spain            | Engineering | -                             | Texture                     | -                    | -                      | -                    | Poorly developed soil |
| Marquez et al. 2017           | [100]    | North America | USA, Iowa      | Other     | -                             | -                           | -                    | Continental soil (Fine-loamy, mixed, supereactive, mesic Cumulic Endosol) | -                    |                |
| Matheson et al. 2002          | [101]    | Oceania   | New Zealand      | Other     | NO$_3^-$, NH$_4^+$            | Bulk density, moisture content | -                    | NZG (1948): Waimango sheepdip soil (northern yellow-brown earth); USDA (1975): Untific Dystristrips | -                    |                |
| Maki & Hopkins 2002           | [102]    | North America | USA, Vermont   | Management  | -                             | -                           | -                    | -                      | Alluvial and lacustrine soils | -                 |
| Meyendorf et al. 2008         | [103]    | Europe    | Belgium          | Other     | -                             | Drainage, texture           | -                    | -                      | -                    |                |
| Neilen et al. 2017            | [104]    | Oceania   | Australia        | Other     | NO$_3^-$, NH$_4^+$, N$_2$O, DON, DOC, SRP in leachate | -                           | -                    | Haplic, Mesotrophic, Red Ferrisols (ASC 2016) | -                    |                |
| Orr et al. 2007               | [105]    | North America | USA, Wisconsin | Other     | O$_3$, NO$_3^-$, N$_2$O, DON, DOC, SRP in leachate | -                           | -                    | -                      | -                    |                |
| Peter et al. 2012             | [106]    | Europe    | Switzerland      | Other     | -                             | Texture                     | Actual denitrification potential, DEA | -                    | -                    | -                |
| Petrone & Posti 2010          | [107]    | South America | Norway          | Engineering | -                             | Texture                     | -                    | -                      | -                    |                |
| Pinto et al. 2016             | [108]    | Europe    | Portugal         | Engineering | -                             | "physical roughness conditions" not further specified | -                    | -                      | -                    |                |
| Rahi et al. 2015              | [109]    | North America | USA, Illinois  | Management  | TC, TN, C/N, plant available P, C-POM | Infiltration, bulk density, moisture retention capacity, texture, drainage | -                    | Swamland (Fine-silty, spodic, mixed, active, minic, mesic Anthropic Udorthents); Loeuland (Fine-loamy, spodic, mixed, active, calcareous, mesic Anthropic Udorthents) | -                    |                |
| Rassam & Pagadoram 2009       | [110]    | Oceania   | Australia        | Management  | -                             | -                           | Denitrification rates  | -                      | -                    | -                |
| Recking et al. 2019           | [111]    | Europe    | "alpine context" | Engineering | -                             | Cohesion, texture           | -                    | -                      | -                    | -                |
| Reisinger et al. 2013         | [112]    | North America | USA, Kansas    | Other     | -                             | -                           | -                    | Ivan (Fine-silty, mixed, supereactive, mesic Cumulic Hapludolls) | -                    | -                |
| Remo et al. 2017              | [113]    | North America | USA, Illinois  | Management  | -                             | Texture, drainage class, water retention capacity | -                    | Soil order (not further specified) | -                    | Data obtained from SSURGO |
| Rheinhardt et al. 2012        | [114]    | North America | USA, North Carolina | Other  | SOM, SOC content | Bulk density | - | - | - | - |
| Rimondi et al. 2019           | [115]    | Europe    | Italy            | Other     | Hg, As, Cr, Pb, Cd, Zn, Cu, Sn, V | -                           | -                    | -                      | -                    | -                |
| Source | #Article | Continent | Country | Category | Chemical Properties | Physical Properties | Biological Properties | Detailed Classification | Other Classification | Other Soil Data |
|--------|----------|-----------|---------|----------|---------------------|---------------------|----------------------|------------------------|---------------------|---------------|
| Rosenblatt et al. 2001 | [115] | North America | USA, Rhode Island | Management | - | - | - | Incertae sedis; Histosols; Entisols | - | - |
| Rosenfeld et al. 2011 | [116] | Europe/North America | Sweden, Finland, Canada | Management | - | - | - | - | - |
| Saad et al. 2018 | [117] | South America | Brazil | Management | pH, TN, TOC, TC; available P, C pools and fluxes | Texture, temperature | - | - | - |
| Samaritani et al. 2011 | [118] | Europe | Switzerland | Other | pH, TN, TOC, TC; available P, C pools and fluxes | Texture, temperature | - | - | - |
| Sgouridis et al. 2011 | [119] | Europe | UK | Other | pH, TN, TOC, TC; available P, C pools and fluxes | Texture (topsoil) | - | - | - |
| Shah et al. 2010 | [120] | North America | USA, New Mexico | Other | pH, TN, TOC, TC; available P, C pools and fluxes | Texture (topsoil) | - | - | - |
| Silk et al. 2006 | [121] | North America | USA, California | Other | pH, TN, TOC, TC; available P, C pools and fluxes | Texture, bulk density, gravimetric moisture | - | - | - |
| Smith et al. 2012 | [122] | Oceania | Australia | Other | pH, TN, TOC, TC; available P, C pools and fluxes | Texture, bulk density, gravimetric moisture | Potential mineralizable N, net nitrification | Red Chromosol (ASC 1996) | - | - |
| Sutton-Grier et al. 2009 | [123] | North America | USA, North Carolina | Other | pH, TN, TOC, TC; available P, C pools and fluxes | Texture, bulk density, gravimetric moisture | Potential mineralizable N, net nitrification | Red Chromosol (ASC 1996) | - | - |
| Tang et al. 2016 | [124] | Europe | Netherlands | Other | pH, TN, TOC, TC; available P, C pools and fluxes | Texture, bulk density, gravimetric moisture | Potential mineralizable N, net nitrification | Red Chromosol (ASC 1996) | - | - |
| Terreni et al. 2015 | [125] | Africa | South Africa | Other | pH, TN, TOC, TC; available P, C pools and fluxes | Texture, bulk density, gravimetric moisture | Potential mineralizable N, net nitrification | Red Chromosol (ASC 1996) | - | - |
| Theriot et al. 2013 | [126] | North America | USA, Arizona | Other | pH, TN, TOC, TC; available P, C pools and fluxes | Texture, bulk density, gravimetric moisture | Potential mineralizable N, net nitrification | Red Chromosol (ASC 1996) | - | - |
| Tian et al. 2004 | [127] | North America | USA, North Carolina | Management | pH, TN, TOC, TC; available P, C pools and fluxes | Texture, bulk density, gravimetric moisture | Potential mineralizable N, net nitrification | Red Chromosol (ASC 1996) | - | - |
| Tesnor et al. 2015 | [128] | North America | USA, Iowa, Illinois | Management | pH, TN, TOC, TC; available P, C pools and fluxes | Texture, bulk density, gravimetric moisture | Potential mineralizable N, net nitrification | Red Chromosol (ASC 1996) | - | - |
| Unghini et al. 2011 | [129] | North America | USA, North Carolina | Management | pH, TN, TOC, TC; available P, C pools and fluxes | Texture, bulk density, gravimetric moisture | Potential mineralizable N, net nitrification | Red Chromosol (ASC 1996) | - | - |
| Source                          | #Article | Continent | Country         | Category | Chemical Properties                                                                 | Physical Properties | Biological Properties | Detailed Classification | Other Classification | Other Soil Data                              |
|--------------------------------|----------|-----------|-----------------|----------|--------------------------------------------------------------------------------------|----------------------|------------------------|------------------------|-----------------------|---------------------------------------------|
| Vandecasteele et al. 2004      | [127]    | Europe    | Belgium         | Other    | Cd, Cu, Zn, Ni, Pb, P, S, TN, CaCl$_2$, OC, pH                                         | EC, texture          | -                      | -                      | -                     | -                                           |
| Walker et al. 2002             | [128]    | North America | USA, Georgia   | Other    | NO$_3^-$, NH$_4^+$, NH$_3$, NO, NO$_2$                                               | Water content        | -                      | Suisnesk (Fine-loamy, mixed, superactive, mesic Humic Hapludults) | -                     | -                                           |
| Walker et al. 2009             | [129]    | North America | USA, North Carolina | Other    | NO$_3^-$, NH$_4^+$, NO$_2^-$, TN, TC                                                  | Moisture             | -                      | Rostam (Coarse-loamy, mixed, superactive, mesic Fluventic Hapludults) | -                     | -                                           |
| Wang et al. 2019               | [130]    | Asia      | China           | Other    | pH, SOM, TN, TP, TK, available N/P/K, Soil microbial number (bacteria, actinomycete, fungi), soil enzyme activity, operational taxonomic units, phylogenetic diversity | Texture, water content | -                      | -                      | -                     | -                                           |
| Wang et al. 2014               | [131]    | Asia      | China           | Other    | NH$_4^+$, NO$_3^-$, NO$_2^-$, N$_2$, TN, NO$_3^-$, in water                           | Texture              | Diversity and distribution of microbial community | -                      | -                     | -                                           |
| Walker & Baker 2014            | [132]    | North America | USA, various   | Other    | NO$_3^-$                                                                              | -                     | -                      | -                      | -                     | -                                           |
| Welsh et al. 2017              | [133]    | North America | USA, North Carolina | Other    | pH, OM, NO$_3^-$, NH$_4^+$, TN, TN, SRP                                             | Moisture, texture    | DEA                    | -                      | -                     | -                                           |
| Welsh et al. 2019              | [134]    | North America | USA, North Carolina | Other    | -                                                                                   | Texture              | -                      | -                      | -                     | -                                           |
| Xiong et al. 2015              | [135]    | Asia      | China           | Other    | pH, OM, TN                                                                           | Texture, moisture, bulk density | -                      | -                      | -                     | -                                           |
| Yu et al. 2019                 | [136]    | Asia      | China           | Other    | Hg, As, Cr, Cd, Pb, Cu, Fe, Mn, Zn, SOM, TP, pH                                     | Moisture, texture    | -                      | -                      | -                     | -                                           |
| Young et al. 2013              | [137]    | North America | USA, Vermont   | Other    | TP, pH, OM, different P speciations                                                  | -                     | -                      | -                      | -                     | -                                           |
| Zaimes et al. 2006             | [138]    | North America | USA, Iowa      | Management | -                                                                                   | Texture, bulk density, permeability | -                      | Spillville (Fine loamy, mixed, superactive, mesic Cumulic Hapludults) | -                     | -                                           |
| Zhang et al. 2018              | [139]    | Asia      | China           | Engineering | -                                                                                   | Texture, shear strength, Root system, root biomass  | -                      | -                      | -                     | Soil map[1:1,000,000] China soil scientific database (soil properties not further specified). |
| Zhao et al. 2013               | [140]    | Asia      | China           | Management | -                                                                                   | Erodibility          | -                      | -                      | -                     | -                                           |
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