soil systems

Review

Forest Soils—What's Their Peculiarity?

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Abstract: Mankind expects from forests and forest soils benefits like pure drinking water, space for recreation, habitats for nature-near biocenoses and the production of timber as unrivaled climate-friendly raw material. An overview over 208 recent articles revealed that ecosystem services are actually the main focus in the perception of forest soil functions. Studies on structures and processes that are the basis of forest soil functions and ecosystem services are widely lacking. Therefore, additional literature was included dealing with the distinct soil structure and high porosity and pore continuity of forest soils, as well as with their high biological activity and chemical soil reaction. Thus, the highly differentiated, hierarchical soil structure in combination with the ion exchange capacity and the acid buffering capacity could be described as the main characteristics of forest soils confounding the desired ecosystem services. However, some of these functions of forest soils are endangered under the influence of environmental change or even because of forest management, like mono-cultures or soil compaction through forest machines. In the face of the high vulnerability of forest soils and increased threads, e.g., through soil acidification, it is evident that active soil management strategies must be implemented with the aim to counteract the loss of soil functions or to recover them.

Keywords: forest soil characteristics; secondary soil structure; soil functions; ecosystem services; spatiotemporal integration level; forest soil management

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1. Introduction—What Are Forest Soils Expected to Be and to Deliver?

The specific characteristic of forest soils is their long-term development under a more-or-less continuous vegetation cover. Trees as long-living organisms and through their magnitude shape soils in a specific way. A, compared to other land-use types, deeper-reaching rooting zone and high activity of microbes, soil fauna and plant roots result in high humus contents, as well as over-proportionally high porosity and continuity of the soil pore system [1]. Forest soils are the habitat of a high diversity of plants, macro-fauna and microbes [2]. Biological networks like the manifold symbioses between trees and mycorrhiza fungi optimize the supply of trees with nutrients and water and enhance the weathering of primary minerals and nutrient release from organic matter, as well as protect tree roots from toxic metal ions like Al^{3+} released through soil acidification [3]. Contamination with pesticides is comparably low in forest soils, since forests are nature-near ecosystems [4]. Moreover, the high demand of trees and soil biota for essential nutrients like phosphorous and nitrogen leads to low leaching rates of those elements in most forest soils [5]. Both the low load with pesticides and low leaching of phosphorous and nitrogen make forests sources of predominantly pure drinking water [6]. Luo et al. [7] found in the subtropical humid Chinese Hunan Province that permanent forest cover has a high potential for erosion prevention combined with a slight increase in water yield.

However, some of these functions of forest soils are endangered under the influence of environmental and climate change or even because of inadequate forest management measures under some circumstances, e.g., the high crown surface of forest combs out acids and nitrogen from air pollution, which leads to severe soil acidification in wide parts of Central Europe and other industrialized regions [8]. Additionally, the use of heavy forest machinery can cause soil compaction, leading to deficits in soil aeration, which can restrict the rooting space for forest trees to the uppermost soil layers [9–12]. Moreover, the optimization of the C-sequestration and greenhouse gas balances of forest soils through specific forest management practices is a topic of high actuality.

This study pursues the following aims and objectives:

1. To work out how physical, chemical and biological properties are interlinked in forest soils and how they define soil functions.
2. To clarify the scale levels of soil functions and ecosystem services.
3. Comparing soil properties under forests and other forms of land use to work out the peculiarity of forest soils.
4. To collect the specific threats on forest soil functions through environmental change and/or management.
5. To give hints for strategies to preserve forest soil functions.

The main emphasis of this study will be laid on making the specific quality and value of forest soils understandable (objectives 1–3). The specific threats and options for soil preservation in forests will be treated in a more exemplary way in the form of an outlook or discussion in order to not make the study too complex.

2. Materials and Methods—Perception of Forest Soils in the Scientific Literature

The literature research for this review was performed in an iterative procedure with stepwise refined and completed research criteria and exclusion of titles that either did not fit the objectives of this study or did not fulfil the quality criteria. A very general first overview on the scientific articles with a focus on forest soils was undertaken when beginning the work of this study on the specific functions of forest soils, their specific vulnerability and forest management options to preserve or restore them. For this purpose, 240 articles were collected with the search keys "forest" + "soil" and with a publication date not older than 5 years. The next step was to check the identified tiles if they fit the objectives of the study. Thus, 32 titles were excluded, mainly theoretical titles dealing with method development or with a too-local focus. According to the expectations on functions, threats and management options on forest soils, six thematic fields were drafted, and the remaining 208 articles assigned to them:

- Soil functions and silviculture: The effects of tree species and stand structures on soil chemical, soil physical and soil hydrological properties are dealt with in this field of interest. Since tree species selection and forest management systems, e.g., clear-cut vs. small-scaled harvesting regimes preserving ample crown cover over all stages of stand regeneration, these fundamental instruments of silviculture substantially influence soil processes [13] and soil characteristics. In this sense, silvicultural strategies can be taken as tools of long-term soil management [14].
- Forest and water: This field comprises the effect of forest soils on the quality and quantity of water yield. All over the world, forested areas are judged to be predominantly suited to provide high-quality drinking water [15]. The second important issue in this field is the function of forest soils as a store of plant-available water resources. This aspect is increasingly relevant under the actual increase of drought periods caused by climate change [16].
- Nutrient availability in forest soils: This item comprises the nutrient pools in forest soils, as well as processes governing the mobilization and availability of nutrients for forest trees.
- Climate change and forest soils: Forests and forest soils are concerned by climate change in two ways. On the one hand, forest soil functions are threatened by extreme weather events like droughts endangering continuous water and nutrient supplies for trees [17,18] or storms and storm floods causing wind throw and erosion damages. On the other hand, forest ecosystems and forest soils can contribute to lower greenhouse gas emissions through carbon sequestration or methane consumption in terrestrial forest soils [19].

- Soil compaction and erosion: Forest soils are in their natural stage over-proportionally unconsolidated and open-pored [12], and erosion is a seldom and subordinate process because of the coherent structure of the forest floor layer and the more-or-less continuous vegetation cover [20]. Therefore, soil compaction and erosion of forest soils are mainly manmade damages. They are caused by machine-bound harvesting techniques or inadequate management techniques like big clearcutting at steep slopes or forest roads and skidding tracks without sufficient water deduction facilities.
- Soil acidification and eutrophication: Soil processes caused by the deposition of acid compounds and nitrogen with precipitation seem to apparently be of minor relevance, since these problems have been somehow cursorily considered in the recent literature. This can be explained because, in the heavily industrialized regions, at least in Europe, the deposition of acidity was substantially reduced through effective filter techniques [21]. However, unnatural soil acidification and its after-effects remained as an inherited problem that still has to be counteracted by ecosystem-conforming measures aiming to rehabilitate the natural functions of forest soils [22,23].

The first three thematic fields deal predominantly with the functionality of forest soils and the last three ones with threats and management approaches for rehabilitation of the functionality of soils in forests.

The overview of 208 relevant articles from the first step of the review process that would potentially fit into the scope of this Special Issue revealed that the six thematic fields are represented with substantially differing intensities (Figure 1).

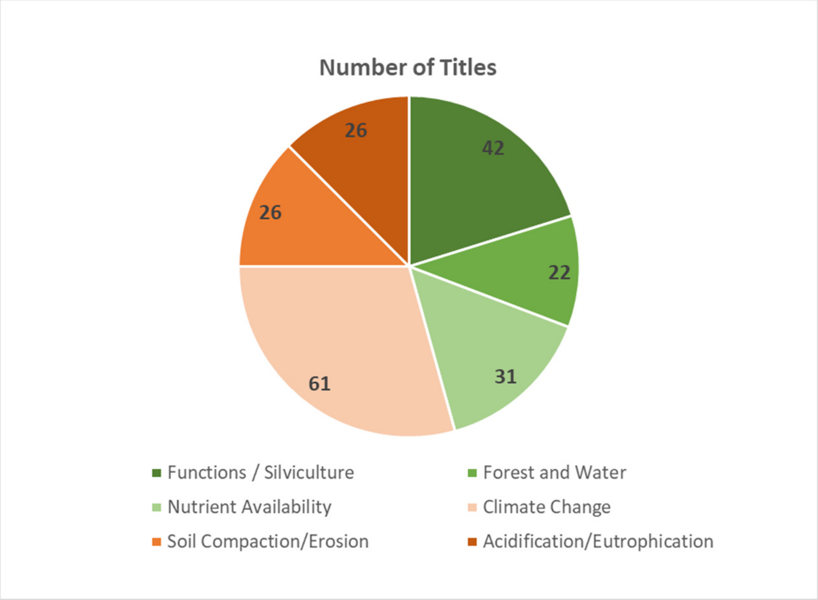

Figure 1. Number of articles in six thematic fields on forest soils and their functions, threats and management. Green colors show thematic fields focusing mainly on the specific functionality of forest soils; reddish colors indicate fields focused on threats to forest soil functions and measures to counteract them.

More than half (54%) of this first overview deals with threats on forest soils and only 46% with the functions of forest soils themselves. The by far dominating share of articles deals with climate change issues and, among them, the main part with the role of forest soils in greenhouse gas budgets. The thematic fields “forest and water”, ”nutrient availability”, “soil compaction” and “soil acidification” are under-represented , respectively, by 15% or less of the titles. Moreover, the thematic focus of the articles in this overview seems, in many cases, not to distinguish between forest soil functions in the narrow sense and forest ecosystem services—the latter staying mainly in the foreground. This is understandable, because ecosystem services concern the effects of forest ecosystems as a whole. They address what mankind expects to receive as goods and services from forest ecosystems. Thus, ecosystem services are commonly perceived to be more relevant as the more abstract soil processes, even if most ecosystem services are mainly defined by soil properties.

Moreover, this first overview on the literature of the last five years revealed that a lot of contributions are focused on small-scaled detail processes like, e.g., microbial activity or the bio-chemical background of the nutrient acquisition of trees, which are, as a matter of course, important processes but provide a somehow scattered view on the specific and fundamental properties of forest soils defining the habitat characteristics, e.g., for microbes.

Therefore, in the second step of the review process, additional titles were included and checked. In order to represent specific characteristics and processes of forest soils and to get a more complete view on the interactions of soil physical, soil chemical and soil ecological processes confounding the specific values of forest soils, 77 additional titles were researched, including 59 older ones. Research-leading ideas were derived from contributions of the working group of Hildebrand on the theory of the "basic regulation unit", combining aspects of the physical soil structure, the chemical "climate" and the biological activity of soils [9] and the theory of Ulrich on the process hierarchy in forest ecosystems [24,25]. For all of these 285 titles, either PDF files were obtained or printed versions were available. Thus, an extensive check of their relevance for the objectives of the study, as well as a quality check, could be performed with a focus on the abstracts, keywords, conclusions and the whole text. An overview on the workflow and selection criteria of the literature research in this study is given in Figure 2.

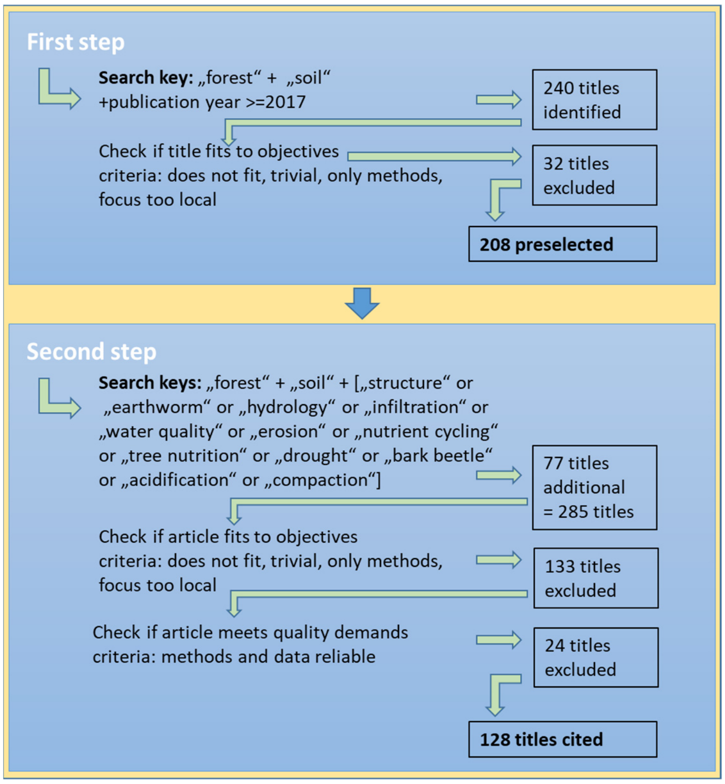

Figure 2. Iterative selection process of the literature research.

The publication years of the remaining 128 articles cited after the final selection are presented in Figure 3. The oldest title cited was published in 1990. Up to 2021, an exponentially increasing number of titles was cited, with 57% in the last five years.

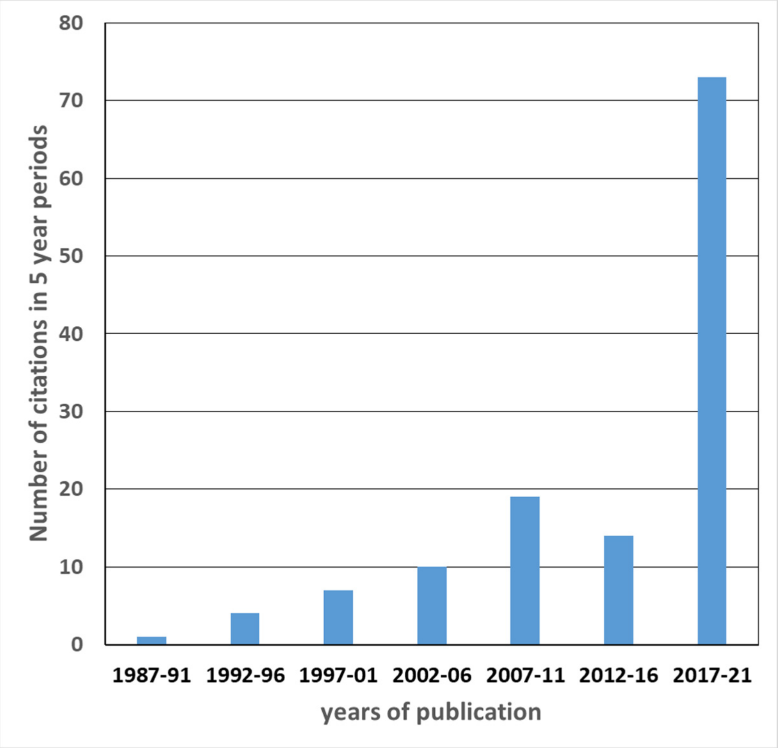

Figure 3. Distribution of 128 titles cited between 1987 and 2021 in 5-year periods.

Moreover, the regional and climatic contexts of the titles cited are given in Table A1. The regional and climatic context of all titles cited in this paper is presented in the Appendix A Table A1 at the end of the paper. The identification of the climatic context was done according to the updated climatic classification by Kottek et al. [26]. The main focus with about 43% of the citations was on temperate-humid and with about 25% on cold-humid climate conditions in Europe where soil genetic conditions are largely comparable and soil functions are not dominated by more-or-less extreme natural boundary conditions like, e.g., subpolar conditions resulting in a dominance of forest floor for soil functions or arid regions with their tendency toward salinification or tropic regions with their susceptibility to nutrient depletion. Those extreme natural conditions were included but in a more exemplary way and were represented with 5–10% of the citations, respectively.

3. Results—Forest Soils, the Basis for Multi-Functionality of Forest Ecosystems

“Natural forestlands are important to conserve soil and water, sequester C, and mitigate net emissions of greenhouse gases while providing wood, fuel, food, fodder, medicines, and other products (e.g., dyes, tannins, perfumes, ornamentals, exudates)” [27,28]. Forest soils are the thin, animated surface of earth where forest trees are rooting. However, they are not only the mechanical anchorage for tree stability rather than a consistent source for the supply of forests with nutrients and water, as well with fresh air for the high oxygen demand of growing roots. Forest soil does not serve only as the supplier for forest growth and, thus, for wood production. Moreover, it is the central “coordinating entity” for most of the ecosystem services that mankind expects from forest ecosystems. A study that was carried out in two contrasting regions in Europe (North–West of Belgium and North–East of Romania) on conditions and strategies to promote soil functions and soil biodiversity stated that “adaptive forest management is currently moving towards management for ecosystem functions and services”, and therefore, “improved knowledge on functions delivered by soil biodiversity” is needed [29]. Complex interactions between chemical, physical and biological soil properties (e.g., nutrient availability, soil acidification and eutrophication, humus accumulation and soil structure) and environmental influences (e.g., atmospheric deposition) are judged by the scientific community to have a high “centrality” (or interconnectivity) to ecosystem services—predominantly to soil biodiversity—but are judged to be significantly less important by forest managers or the public. However, the importance of ground vegetation, tree species choice and nutrient cycling was judged by both communities synchronously to be comparably high, and the importance of climate conditions, recreation activities, timber production and harvesting was judged to be low [29]. This study revealed that strategies for preserving soil functions in a sustainable way need multivariate modeling approaches on a sound basis of quality-checked data (particularly from well-defined monitoring systems), as well as thorough transfer and communication of the results to practitioners and the public.

3.1. Soil Properties and Processes Founding Forest Soil Functions

The characteristics of forest soils are, on the one hand, shaped by long-lasting forest cover, the specific characteristics of matter cycles and dominated by high carbon input in forests, as well as by largely closed element cycles. On the other hand, the distribution of land use types in landscapes is not random. Agricultural land use types are preferentially situated on deeply developed soil types with high water holding capacities and high nutrient stocks, whereas for forests, the less fertile locations remain. Burst et al. [30] found in NW France that "forests were usually located slightly upslope of grasslands, and mainly because this non-random topographic position the topsoil texture was significantly more silty in forests, and clayey in grasslands", resulting in a higher soil porosity in forest soils that also persists after deforestation and land use changes to grasslands.

Forest soils are the overlapping space where the atmosphere, pedosphere and hydrosphere are closer interlinked among each other, as in soils of most other land use types, since the soil structure is predominantly fine-scaled in forest soils. They are the "reaction vessel", where the weathering of primary minerals to pedogenic substances, as well as the organic and nutrient matter cycles, take place, where the buffering of acids; storage of substances and their transformations between the solid, liquid and gaseous soil phases occur [9]. Thus, on-site effects like the filter, buffer and habitat functions of forest ecosystems are mainly directed by soil processes, as well as their function as sustainable breeding grounds of the climate-friendly raw material timber. Moreover, soil processes are the basis of off-site effects like the ability of forest ecosystems to mitigate climate change through their ability to minimize greenhouse gas concentrations by stable carbon storage predominantly in mineral soils, as well as by methane consumption and minimizing nitrous oxide efflux. Several studies demonstrated that, in forest soils, higher carbon pools are stored in comparison to arable or grassland soils [31–33]. A study in Central Poland revealed that the nitrous oxide emission was about three times lower from forest soils as from arable land [34], and Täumer et al. [35] derived from comparing 150 grassland/forest pairs that "reduction in grassland land-use intensity and afforestation has the potential to increase the CH_4 sink function of soils". Another crucial function of forest soils is to deliver high-quality drinking water and to equalize the landscape hydrology or even the resistance of forest soils against soil erosion [20,36].

3.1.1. Secondary Soil Structure—The Spatial Frame of Soil Functions

Forest soils are well-structured at different hierarchical levels. At the level of soil profiles, they are characterized by pronounced vertical layering. The specific characteristics are the high contents of organic materials in the humus layer and the upper A-horizon caused by the high litter input from the crown layer. The long-lasting forest cover allows for a more-or-less evolutionary development of a complex secondary aggregate- structure in mineral horizons of forest soils. Mainly, the activity of an abundant community of soil fauna does mix the mineral and organic components of the soil solid phase and forms secondary soil aggregates. Zangerle et al. [37] demonstrated with mesocosm experiments that "earthworms and plant roots, as ecosystem engineers, have large effects on biotic and abiotic properties of the soil system. They create biogenic soil macro-aggregates (i.e., earthworm casts and root macro-aggregates) with specific physical, chemical and microbiological properties”. The initial formation of soil aggregates also results from abiotic processes like shrinking in drought periods, freezing or flocculation under the influence of multiple-charged cations. “Biologic activity is one of the main factors controlling the floating equilibrium between loosening and compacting forces in humic forest soils” [38]. Through the digging activity of soil fauna and growing roots, a high soil porosity with an over-proportional connectivity is created. Undamaged forest soils provide a significantly higher macro-porosity than cropland soils [39]. Sokołowska et al. [1] examined in the Carpathian region soil properties in a succession from meadow to mature forests. They found that “forest succession increased the soil porosity in the 10–20 cm layer, especially the volume of macro pores” and increased carbon sequestration on the long term. Damptey et al. [40] found after two decades of forest restoration on former mine areas in Ghana significantly increased carbon contents and decreased bulk density in the mineral soil. Zhang et al. [41] found in tropical forests in the Philippines that the bulk density was higher and porosity marginally lower in grasslands than in afforested areas, resulting in avoiding the Hortonian overland flow, which commonly occurred in the grassland areas.

The high porosity and the secondary aggregate structure is a dissipative and dynamic steady-state equilibrium that can only been maintained by continuous energy input from biologic activity against sagging forces [9]. The fundamental benefit of this complex soil structure is that it provides within elementary soil volumes a few mm^3 wide quasi-simultaneously and quasi-at the same locations water, nutrients and oxygen in plant-available forms. This seems to be contradictory on first sight but is realized by the close vicinity of meso-pores binding plant-available water, clay minerals storing exchangeable nutrients and nonwaterlogged macropores allowing for oxygen supply and carbon dioxide discharge (Figure 4). Thus, unlike sediments, the secondary structure is one of the most essential properties of forest soils, and it can serve to fulfill these quasi-contradictory needs of plant growth and the productivity of forests [9]. The distribution of roots is restricted to the surface zones of soil aggregates and macropores because of the high oxygen demand of growing roots.

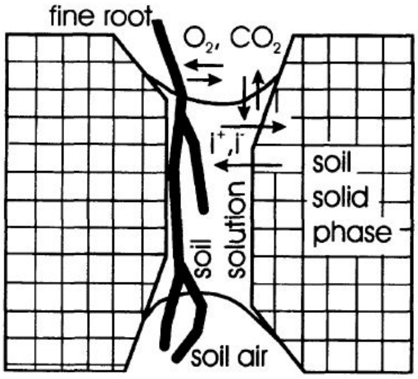

Figure 4. Basic regulation unit of soils in the range of a few mm^3 controlling the dissolution of minerals and organic matter, the transport of diluted compounds (i$^+$ and i$^-$) and simultaneously enabling the oxygen supply and carbon dioxide discharge. Thus, within these small, well-structured soil volumes, all essential demands for root growth are given under normal conditions: supply with water and nutrients, as well as sufficient aeration (from Reference [9]).

Since external mycorrhiza hyphae have diameters of 2–10 µm by one order of magnitude smaller than fine roots, they could potentially enter the mesopores of the intra-aggregate space. However, Schack-Kirchner et al. [42] and, also, Witzgall et al. [43] found in mesocosm experiments with naturally structured soil cores that hyphae also open the intra-aggregate space of forest soils very inefficiently, and thus, they do not show different behaviors than roots or aerobic microorganisms (Figure 5).

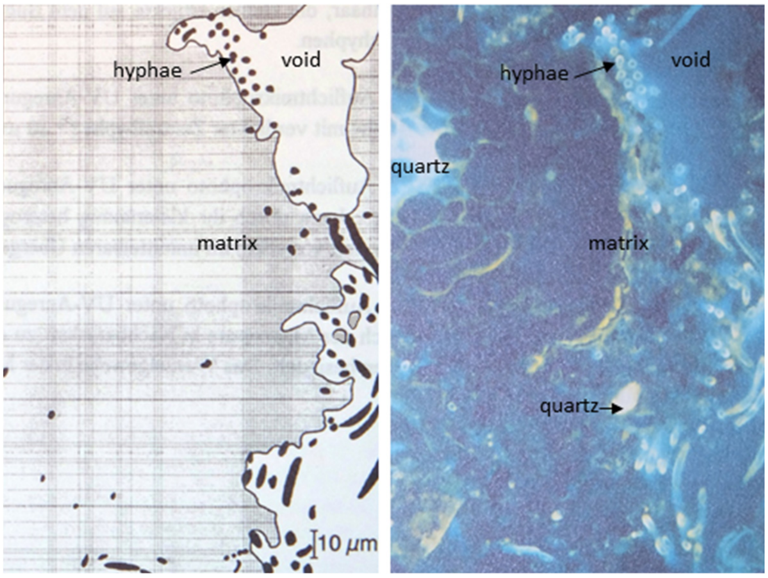

Figure 5. Evaluation of the soil preparations embedded in polyester resin polished and stained with acridine orange. Left: results of the object identification with the picture analysis system Leitz CBA 8000 at display windows of ca. 250 µm edge length. Hyphae and root fragments (black), soil matrix (grey-shaded) soil pores and voids (white). Right: micro-photo of the same display window reflecting light with UV activation (according to Reference [42]).

"The major part of hyphae grow within macro pores (>10 µm)" and "of the hyphae in the soil matrix, 70% were located in a 50 µm shell around the macro pores". It could be substantiated with geostatistical methods (e.g., pair correlation functions) that the hyphae in macropores and at the superficial shell of soil aggregates are heavily clustered (see the example in Figure 5). "Therefore, a considerable amount of chemically available nutrients is not directly accessible for the roots" [42]. This can cause deficiencies in the nutrient supply, especially in drought periods when the diffusive replenishment of aggregate surfaces with nutrients is interrupted when the waterlogged intra-aggregate pores dry out. "On the other hand, the inaccessibility of the intra-aggregate space by organisms can also be seen from a positive point of view. Storage of nutrients in intra-aggregate pores can be regarded as an efficient mechanism to prevent the highly mobile water-soluble ions from leaching" [42].

3.1.2. Soil Chemical Status

Most forests are not fertilized, disregarding artificial plantation forests. Therefore, the primary sources of chemical elements and nutrients are input fluxes with precipitation and the weathering of primary minerals, which is, in most forest ecosystems, the dominant input flux. Since weathering is a very slow process, it cannot equalize short-term fluctuations of the forest nutrition, e.g., caused by weather fluctuations like drought [24]. Clay minerals and clay–humus complexes provide negatively charged exchanger surfaces that adsorb cationic, basic nutrients (calcium, magnesium and potassium), as well as cation acids (aluminum, iron, manganese and ammonium). Thus, soils serve as short- to medium-term stores for plant-available nutrients, providing more-or-less constant nutrient availability for forest vegetation and trees, which can bridge such externally driven gaps in nutrient supply. An additional buffering function in the nutrient supply of forest stands can be fulfilled by the nutrient store in the humus layer and its mobilization by mineralization [24].

Soils naturally acidify in the course of soil development, but that is a very low process (e.g., in Central Europe under temperate–humid climate conditions, the mean soil acidification, since the last glaciation period, caused a pH decrease of 1 to 2 pH levels in about 10.000 years). This can be judged as a quasi-steady state [44].

If the saturation of exchanger surfaces with cation acids becomes dominant as a result of soil acidification, the selectivity for basic nutrients drops exponentially. Subsequently, essential basic nutrients are leached with seepage water accompanied with anions of carbonic acid or under the influence of air pollution and “acid rain” with the strong mineral acids sulfate and nitrate. This depletion of essential nutrients is highest for magnesium, since its bond strength to soil exchanger surfaces is predominantly low [45]. The transport pathway between the exchangeable ion pools and plants and/or seepage is the soil solution. Other relevant transport pathways of the element cycle are the mobilization of elements directly from organic materials or from inorganic minerals. This is the dominant source for tree nutrition with phosphorus, sulfur and, also, partially nitrogen, which is closely coupled with the cycle of organic substances [24,46]. The acid/base relation as expressed by the base saturation (relation between exchangeable cation bases and cation acids) is judged as an integrating indicator on the buffer function of soils, similar to the soil reaction (pH value). Both are constitutive parameters for the habitat quality for soil microbes and soil fauna [47]. Especially struck by soil acidification are earthworms, which are important as engineers of the soil structure, mixing organic material with mineral soil, enhancing the decomposition of organic material, forming stable soil aggregates, providing habitats for microorganisms [48] and creating highly continuous macropores enhancing soils aeration and water infiltration [49].

Since forest mineral soils are not a coherent paste or a slurry, the soil structure varies the mobilization and transport of chemical elements substantially like, e.g., the heterogeneous distribution of exchangeable nutrients in well-aggregated acid forest soils suggests, where concentrations of potassium, magnesium and calcium were found to be depleted at aggregate surfaces and high in the intra-aggregate space. The recharge of ion pools at the aggregate surfaces was substantially delayed, particularly for potassium [50]. This can be interpreted as an interaction between soil structure and chemical exchange kinetics and underlines the ecological value of the secondary soil structure and its predominant relevance for forest soil functions. The manifold interactions between soil chemical properties, soil structure and soil biological activity suggest that the full multifunctionality of forest soils requires the mutual optimization of those three aspects. This optimization process occurs in undisturbed forest ecosystems through evolutionary approximation to an attractor space being defined by climate, geology, soil development, soil texture, topographical position and species composition of the tree and ground vegetation layers. In managed forests, this approximation can either be supported or disturbed by management measures.

3.2. Forest Ecosystem Services

Soil processes confounding soil functions and, subsequently, ecosystem services of forests are defined by physical, chemical and biological soil properties and the interactions among them. Ecosystem services are related to higher spatiotemporal integration levels as soil functions. The typical spatial scale for ecosystem services is the pedon (area where soil characteristics are comparable) to catchment or landscape scales. The temporal scale for their generation is the mean life cycle of forest stands. Both are definitely macroscales compared to the meso-scaled dimension of the basic regulation unit being responsible for soil functions (Figure 4). The formulation of ecosystem services represents the benefits that mankind expects to be provided from forest ecosystems, which is a typically anthropocentric point of view.

3.2.1. Forest Soils as Basis for Growth and Existence of Forests

Forest soils are the basis for the growth intensity of forest trees and thus provide regenerative and climate friendly raw material timber. Between soil properties and forest trees, there do not exist simple and monocausal cause/effect relations rather than mutual influences and adaptations between trees and soil properties. On the one hand, soil properties define how tree species can grow and how they can assert themselves against the concurrence of other tree species. On the other hand, tree species are able to shape soil properties in an active way in order to optimize habitat conditions like, e.g., nutrient availability. The latter is the predominant factor under unfavorable environmental conditions. The supply with nutrients and water are the crucial variables of forest growth and are primarily determined by site characteristics like the geological provenience of bedrock, soil development and climate. Thus, site characteristics determine the ecological niches of forest trees. "Soil-sensitive tree species in temperate forests like ash or sycamore were found to be much more sensitive to soil variables than European beech. The most relevant soil variables for the competitive ability of the three species were found to be C/N-ratio, humus form, aluminum content, base saturation, magnesium content, and soil aeration. Shortage of nutrients limited the distribution of ash and sycamore and excess of toxic elements the distribution of ash" [51]. The supply of trees with mass nutrients like magnesium, potassium and calcium is closely linked to soil acidification when strongly adsorbing aluminum cations suppress adsorption of the nutrient cations at soil exchanger surfaces [50]. Furthermore, the secondary soil aggregation varies the plant availability of these nutrients [50,52]. This also applies for mycorrhiza hyphae, which are commonly described as spatial extensions of the reach of the rhizosphere of trees, since hyphae are, like roots, not able to enter the inner parts of soil aggregates (see Figure 5 and Reference [42]).

Since forest soils are, compared to soils of other land use forms, less fertile and mostly stonier [30], therefore, the potential contribution of the soil coarse fraction to the nutrition of trees and forest stands shall be considered in a short paragraph. Conventionally, nutrient pools in fine soil material (corn size < 2 mm) are taken as the dominant source of tree nutrition. However, under specific conditions like, e.g., in acidified and nutrient depleted podsols, the nutrient pool in the coarse soil fraction also seems to be accessible to trees, since "EcM fungi can" actively "dissolve mineral grains" [53]. Heisner et al. [54] found in heavily acidified forest soils of the Black Forest (SW Germany) that the skeletal fraction has a cation exchange capacity (CEC) within the same order of magnitude as fine earth. This finding was assumed to be attributed to fine material-filling fissures of skeleton grains. Koele et al. [55] substantiated this hypothesis and showed that "fine earth accumulated within the weathering fissures of the coarse-soil fraction (particles > 2 mm), so called stone-protected fine earth, can provide a high, short-term nutrient release by cation exchange". They could also demonstrate that "in the coarse-soil fraction of the BhBs horizon, the absolute hyphal length exceeded the hyphal length in the fine earth by factor 3" [56]. They concluded from their studies that "exchange processes were the main trigger of Ca and Mg mobilization and uptake rather than protolytic weathering by exudation of carboxylic acids", like van Schöll et al. [53] stated: "The exchange processes may be attributed to weathering cracks filled with fine material of high base saturation" [57]. These findings imply that the exchangeable nutrient pools in fine earth and "stone protected fine earth" in forest soils should be treated as a continuum when assessing the base cation supply of forest stands. However, since the mobilization of nutrients from primary minerals through weathering is a very slow process [58] that could recharge the exchangeable nutrient pool in stones, the use of these pools must be judged as a short-term emergency strategy to bridge a nutrient shortage, e.g., caused by the fast-developing soil acidification of the last decades in silicatic soils of Central Europe.

The supply of trees with nitrogen and phosphorous, which are predominantly essential nutrients for forest growth, is closely linked to the organic matter cycling in forest ecosystems and microbial activity. Waldner et al. [8] derived from the Europe-wide intensively monitored forest plots (Level II) that critical loads for inorganic nitrogen deposition were exceeded on about a third to one-half of the forest plots, which leads, on the one hand, to nutrient imbalances, such as low magnesium and potassium concentrations in foliage. On the other hand, a tendency toward elevated nitrate concentrations in the soil solution was observed at these plots, which propagates soil acidification and base cation export. Thus, nitrogen nutrition is, in Central Europe and other regions with high nitrogen deposition, no more a limited nutrient rather than an exuberance problem. In tropical forest ecosystems in Guinea, strong positive correlations were found between soil clay contents and total soil carbon stocks, as well as minerals associated C, N and P stocks, which were also correlated with mycorrhiza abundance, growth dynamics and the mortality of forest trees [59]. In stands of Chinese Fir, the microbial limitations of the mineralization of organic matter and organic phosphorous were found to be associated with the microbial demand of nitrogen [60]. The P-acquisition strategy was examined in stands of European beech in Germany. In P-rich soils, plants and soil organisms mobilize P mainly from primary and secondary minerals. In P-poor soils, roots and fungi seem to sustain their P demand more successfully than bacteria, mainly from the forest floor and soil horizons rich in organic matter. This underlines, in principle, a high adaptability of beech forest ecosystems to changing P supplies. Thus, "P deficiency is unlikely the result of a low P supply per se. More likely, sufficient P nutrition depends on supply-specific plant–microorganism–soil interactions" [46]. Moreover, it was found in this study that the phosphorous in particulate soil organic matter (SOM) within aggregates tends to increase with the decreasing soil P stock. That indicates that physically protected particulate SOM becomes increasingly relevant as a P cache in soils with a declining P status [61]. Additionally, Rodionov et al. [62] found "that P deficiency in the surface soil not only fosters microbial cycling of P in the organic and upper mineral soil layers but also causes the utilization of P from the deeper subsoil", and they concluded that "with continued weathering of the bedrock and mobilization of P from the weathered rocks, P cycling will proceed to greater depths, especially at sites characterized by P limitation". The complex interaction of chemical, microbial and physical processes in P cycling in forest soils is actually referenced for a large variety of ecosystems with a large number of publications (e.g., References [63–66]).

The second important factor of forest growth and health status besides nutrient supply is a widely continuous water supply. Compared to arable soils, the surface layers of forest soils (forest floor and upper A-horizon) have high humus contents and much more openpored mineral soils, maximizing water infiltration and, thus, minimizing the occurrence of surface flow [20]. Soils act, as for nutrients, for water also like a "buffer store" enabling a high continuity in supply. Forest soils are able to maintain a site-specific water status caused by the nonlinearity of the unsaturated water conductivity function, which decreases exponentially with the decreasing pressure head. As a consequence of heavy rain events, water enters macropores, where the surplus water that gets not quickly stored in the meso- and micropores leaves the rooting zone quickly as seepage water. Thus, sufficient aeration in the rooting zone is also guaranteed in periods of heavy rainfall. The water in the meso- and micropore spaces gets retained against gravity over a long time and, thus, can, at least partially, sustain the water supply of trees during drought periods. Both the nutrient and water supply are directly related to the soil volume being opened up by roots and mycorrhiza hyphae and, thus, to the extent of the rhizosphere.

3.2.2. Secondary Ecosystem Services

Forest soils are the basis for manifold ecosystem services, besides growth and the existence of forest stands themselves. They serve as habitats of a broad variety of fauna [67,68], plants of the ground vegetation [2], fungi [69] and microbes [70]. Close interactions between the composition of the herbaceous ground vegetation and soil microbial diversity were found to drive forest ecosystem functioning in European temperate forests [2]. Giguère-Tremblay et al. [71] highlighted in boreal forests the "predominant role of soil organic matter on multi functionality . . . even though microbial diversity is important". Friggens et al. [72] found in boreal forests in Sweden "no trend in respiration with distance from trees, likely mediated by an extensive root and ectomycorrhizal network of the birch trees, which efficiently exploit resources throughout the forest". Strong correlations between dominant tree species and fungal communities were found on the local scale in mixed boreal stands (trembling aspen/black spruce) in Western Quebec [73]. Lots of soil functions and the ecosystem services linked to them are generated or at least influenced and shaped by these biota [37]. The adaption of these populations to the boundary conditions of site quality, climate conditions and phases of stand development is a slow process in the range of months to decades compared, e.g., to the very fast chemical exchange reactions. Thus, the integrity of the habitat function of forest ecosystems depends on the fact that, in not substantially disturbed cases, changes in boundary conditions are so slow that the biota can follow. This is, e.g., realized by the quasi-circular coevolution of animal communities, humus forms and mineralization processes along three stand phases of spruce in the Italian Alps [67]. Summarizing, it can be stated that forest ecosystems commonly provide a higher biodiversity and higher microbial activity [1] than agricultural land use types or forest succession on former agricultural land.

The high porosity and intrinsic surface in combination with their exchange capacity qualify forest soils as effective filters for water [74]. Especially along the passage through extensively rooted soil layers, potentially harmful substances for water quality are retained, adsorbed and/or transformed to less harmful compounds through chemical or biological soil processes. Phosphorous gets, e.g., in acid soils with high Al activity, quantitatively fixed by forming Al-phosphates and/or is quantitatively taken up by plants and microbes in the uppermost soil layers [46]. On the other hand, Missong et al. [75] indicated that 12 and 91% of the totally leached P from 20-cm-long soil columns were bound mainly to nano-colloids (0.6–29 nm) and fine particles (70–400 nm), depending on the type of the forest soil. They found that "size and composition was comparable to colloids present in acidic forest streams known from literature". Markowski et al. [5] observed during heavy rainfall events following dry periods a depth transport of P into the subsoil along preferential flow paths, especially for particle-bound P. Thus, evidence was obtained that P leaching from forest soils to the hydrosphere feasibly occurs, even if P–retaining soil processes are strong and effective. Nitrate is in anoxic soil layers subject to microbial denitrification and leaves the soil as gaseous nitrous oxides or elementary nitrogen [76]. Some tree species like European beech can quantitatively take up nitrate from the seepage water and, thus, act as effective nitrate sinks [14] and subsequently enhance the water quality even under the actual deposition conditions in Central Europe. Sucker et al. [77] explained the actual decreasing nitrate concentrations in headwater streams of the Ore Mountains with "a higher N uptake as a result of extensive reforestation and the continuous recovery and increasing vitality of damaged forests". Generally, forest soils provide an above-average infiltration capacity because of the very high porosity of the surface soil layer. Compared to agricultural land use, the infiltration rates in forests are 200–500% higher [41,78,79]. Thus, they prevent fast runoff on the soil surface or as surface-near interflow, which is predominantly relevant under tropical conditions with high precipitation intensities. This helps to minimize flood events in forest lands. Additionally, the protection of the soil surface by humus layers and ground vegetation is an effective security against soil erosion. Zhang et al. [80] found in a field experiment in the Loess Plateau (NW China) under grassland about 50 times and under arable farmland 100 times more eroded soil sediment after 30 min of heavy rainfall with 120 mm h^{-1} intensity as compared to forest land.

Recently, the role that forest ecosystems play in the context of climate change becomes more and more focused on by scientists and the public, as the high number of contributions to that thematic field imply (Figure 1). The most important contribution of forest ecosystems and forest soils for counteracting climate change is to sequester and/or metabolize greenhouse gases or components of them. The most important factor is carbon sequestration in forest stands as plant biomass or, subsequently, in the soil as organic matter on the forest floor and in the mineral soil (SOC). Witzgall et al. [43] stated that "The largest terrestrial organic carbon pool, carbon in soils, is regulated by an intricate connection between plant carbon inputs, microbial activity, and the soil matrix. This is manifested by how microorganisms, the key players in transforming plant-derived carbon into soil organic carbon, are controlled by the physical arrangement of organic and inorganic soil particles". This statement underlines the significance of the interaction of the structure, chemical status and microbial activity for the functionality of soils and ecosystem services. Caddeo et al. [33] modeled (Century5 model) for all of Italy the present soil carbon stocks and projections to the year 2095 under different agro-ecosystems and forests. They found that the current SOC stock estimates range from 51.3 in orchards to 129.5 Mg carbon ha^{-1} in coniferous forests. Projections under the influence of climate change (scenarios RCP4.5

and RCP8.5) "showed a moderate carbon loss suggesting that forest, grassland, and permanent crop soils could provide an important contribution to climate change mitigation". Pellis et al. [81] compared SOC and above-ground biomass in a 62-year-old forest afforested on former grassland, with the carbon pools in an adjacent grassland in the Italian Alps and the Apennines. They found under 62-year-old afforestation about two-times higher SOC stocks than under the correspondent grassland. In the Apennines with dryer and warmer climate conditions, the SOC increase was much higher than in the Alps. Additionally, the carbon stock in the above-ground biomass amounted in the old forest stands to 100–170% of the SOC stock. Moreover, this study highlighted the importance of considering the subsoil, since deep soil layers contributed 38% to the observed variations in the carbon stocks after land use change. Kalks et al. [82] found in three beech stands in Germany on sandy to loamy soils that 13C-labeled DOC injected at three soil depths was, after 17 months in the topsoil, largely lost (−19%), while DOC in the subsoil did not change much (−4.4%). The data indicated a high stabilization of injected DOC in the subsoils with no differences between the sites. This supports the significance of the subsoil carbon pool for long-term carbon sequestration. A study by Wordell-Dietrich et al. [83] supported this thesis, since they found in beech forests in Northern Germany that most of respired CO_2 (90%) was produced in the topsoil (<30 cm). However, the subsoil (>30 cm), which contained 47% of the SOC stocks, accounted for only 10% of the total soil respiration. Zachary et al. [84] determined SOC turnover rates by incubating trials with a silt loam-textured Luvisol from West Hungary. They determined the mean residence time (MRT) of four different SOC fractions. The particulate organic matter fraction was found to be the most labile C pool with a MRT of 3.6 years, and the most stable fraction was the chemically resistant soil organic carbon fraction associated with clay particles with MRT of 250 years. Forest continuity is obviously also an important factor for preserving high SOC pools. In NE Germany, significantly larger total SOC stocks were found in ancient forests (age > 200 years) as compared to 100–200 year-old afforestation. These differences were obtained partially in subsoils at depths of between 29 and 55 cm. Soils of "ancient" beech and pine forests stored, on average, twice as much SOC in the subsoils than did "old forests" [85]. In Denmark, also, a tendency toward increasing SOC stocks with increasing stand age after afforestation was found [86].

Besides carbon sequestration, the budget of methane (CH_4) and nitrous oxide (N_2O) of forest soils is highly relevant, because their greenhouse potential is much higher than carbon dioxide. According to the IPCC Fifth Assessment Report [87], the relative global warming potential (for a 100-year period) of CH_4 28- and for N_2O is 265 times as high as for CO_2. Undisturbed terrestric forest soils are a weak source of N_2O and a weak sink for CH_4 [88]. From wet soils, the emission of N_2O is much higher [89]. Schindler et al. [90] showed in a flooding experiment that soil water and nitrogen contents are the main controlling factors of stem and soil N_2O- and CH_4 fluxes. During flooding, CH_4 emission increased by a factor of 10, and the weak CH_4 sink turned to a strong source. The N_2O emission increased during flooding by 40%. Sosulski et al. [34] found in Central Poland that the N_2O-N emission from the arable soils is about 30% higher as compared to forest soils due to a greater amount of mineral nitrogen available for the nitrifying and denitrifying bacteria in the arable soils. They concluded that "conservation and sustainable management of forests would constitute an effective way to mitigate the N_2O-N emissions from the soil".

4. Outlook and Conclusions

After the detailed description of the functions of forest soils and ecosystem services of forests in the Results section, a short overview shall be given here on the actual threats on the integrity and functionality of forest ecosystems, as well as on the management options to counteract them. Some concluding remarks will summarize what forest soils differentiate from soils under other land use types.

4.1. Threats to Forest Soil Functions and Ecosystem Services

With respect to the high complexity and multifactorial boundary conditions of the functions of forest soils, as well as on the large scale of forest ecosystem services, it is intuitively understood that the vulnerability of them is high. Like their functionality, their threats are specifically branded by the characteristics of forests. A large crown surface, e.g., causes a high transpiration demand, which can provoke drought, and the height of trees is related to windthrow vulnerability. The main natural hazards are storms, insect calamities and their after-effects like increased fluxes of nitrate and phosphorous, which can endanger the water quality [91], and wildfire. Wasak et al. [92] found that windthrow does not only reduce the growth intensity of forest stands rather than also microbial activity. Reduced microbial activity after windthrow was predominantly attributed to a breakdown in fungal activity, which can be explained with a lack of substrate that feed trees to mycorrhiza fungi in undisturbed stands. These natural hazards are in the natural stage of site conditions to which tree species are evolutionarily adapted.

However, mankind accelerated soil processes like acidification and changed quasi-stable boundary conditions like climate characteristics to an amount that does not allow for the easy adaptation of trees. Additionally, forest management itself can contribute to manmade ecosystem damages, e.g. by the deformation and compaction of soils through moving heavy forest machines on unprotected soils. Kohler and Hildebrand [45] described this phenomenon as four unintended, large-scaled ecosystem experiments: the "titration and eutrophication experiment" with forest soils in Middle and Northern Europe yielded a drastic and self-accelerating depletion of exchangeable basic cations, "since bond strengths of exchangeable earth alkali ions decrease with increasing acidity". The drivers of soil acidification are the activity of strong and mobile acid anions—predominantly nitrate and sulfate. Even if, e.g., in Central Europe, the deposition of sulfate dropped in the last decade below the critical load threshold, the deposition of nitrogen remains high, causing, e.g., imbalances in tree nutrition and the ruderalization of ground vegetation [70]. Soil acidification, however, still persists as an inherited problem that results in a tendency towards flat rooting systems, thus increasing the susceptibility of trees for drought and disturbing tree nutrition when the potential rooting space is only partially exploited by roots like Matzner and Murach hypothesized [93]. The most threatening biological consequence of soil acidification is the drastic reduction of earthworm abundance at pH values below 4.5 [48], because earthworms are the main agents of the secondary soil structure [49], which is a key factor of soil function (see Section 3.1.1). Moreover, the progress of the acidification front towards the hydrosphere increases the risk of deterioration of the water quality and habitat characteristics of streams and lakes [77]. The "soil deformation experiment" [45] results in drastically reduced soil aeration and, thus, in a substantially reduced rooting intensity [10]. The recovery of compacted soils lasts decades [94]. Moreover, the shift from aerobic to anaerobic metabolism in compacted soils suggests that skid trails may be unconsidered hot spots of greenhouse gas balance because of substantially increased N_2O emissions and decreased CH_4 consumption, both due to the locally anaerobic soil conditions in skid trails [95,96], thus creating a link to the "greenhouse experiment" [45]. Climate change leads to warming and the increased frequency and intensity of extreme weather events threatening the existence and functionality of forests. Büntgen et al. [97] found in tree ring analyses that the sequence of recent European summer droughts since 2015 is unprecedented in the past 2110 years. Boden et al. [16] found in spruce forests in SW Germany that drought is an increasing threatening factor there and that the cumulation of drought events decreases the resilience of spruce to drought stress. Fleck et al. [98] derived from model projections that nitrate leaching from forest soils will increase because of increased organic matter decomposition. Hennings et al. [99] found that riparian areas in tropic rainforests in Sumatra have a high potential for C-sequestration and but a high C-loss potential if drained.

The impacts of environmental change on soil and ecosystem functions are complex and cannot be understood and managed in monocausal approaches. The complex interactions between climate change effects and soil functions and the large-scaled ecosystem services will be pointed out with the example of the actual forest dieback caused by climate change and its subsequent after-effects. This consideration will be focused on Europe, because there not only the direct effects of climate change are relevant rather than their interactions with the deposition history. Puhlmann et al. [100] modeled in Germany a significant increase of drought events since 1990 in terms of soil water availability. If "soil acidification and increased N availability decreased the fine root biomass of trees and shifted the rooting zone to upper soil layers" [93], this would aggravate drought stress for trees. In the Swiss Alps, a differential diagnostic study revealed that the actual tremendously increasing mortality through bark beetle attacks even in higher elevated areas (up to 1700 m a.s.l.) is not related to increasing bark beetle virulence or the raisin defense weakness of trees rather than to "drought-induced reduction in tree vigor ... under the ongoing climate warming" [101]. Rewald found that oak (*Quercus petraea*) and beech (*Fagus sylvatica*), as the two naturally dominating tree species in Central Europe, show very high vulnerability of fine roots to die off during drought events and thus prolong drought damage [102]. Additionally, in Switzerland, a study on the drought tolerance of trees stated that the "premature mortality of roots" leaves trees more vulnerable following drought years [103]. The same aspect was addressed by a modeling approach in the USA and Sweden that revealed that "host tree vulnerability plays an important role in bark beetle outbreak intensity" [104]. A study covering a climate gradient from Southern Sweden to Mediterranean Europe identified temperature warming, drought and storm effects as key climate drivers of the actual intensity of bark beetle calamities [105]. These studies provide evidence that an important determinant of tree mortality resulting from drought and subsequent bark beetle calamities is the predisposition of trees by deterioration of soil functions. Thus, it seems likely that the actual intensity of drought and bark beetle damages in Europe, Scandinavia and other industrialized regions is the result of the interrelation between predisposing stress factors arising from soil acidification/eutrophication and increasing climate stress. A study on long-term environmental monitoring data in Switzerland found that cation leaching losses actually mainly driven by nitrogen deposition are endangering forest sustainability. "Soil acidification has negative consequences for forest health, such as increased risk of windthrow on soils with low base saturation <40% or decreased rooting depth for soils with a base saturation <20%" [106]. Thus, the acidification legacy of former acid deposition and ongoing nitrogen deposition destabilizes forest ecosystems. It is reasonable to assume that predisposing and acute stress factors are acting together in an additive way.

4.2. Management Approaches for Protecting the Functionality of Forest Soils

In the face of the high vulnerability of forest soils and their functions and especially in industrialized regions, increased threats, e.g., through soil acidification, the loss of processes generating and maintaining the secondary soil structure and, thus, the loss of forest soil functions, it is evident that active soil management strategies must be implemented with the aim to counteract the loss of soil functions or to recover them as far as possible. At least the irreversible loss of soil functions like the destruction of clay minerals through heavy soil acidification must be avoided.

4.2.1. Silvicultural Management Options

The most important silvicultural management options are tree species selection and harvesting, respectively, thinning regimes. Several studies suggest that these management options would have different potentials for soil preservation besides the ostensible task of silviculture to optimize forest growth. The most fundamental silvicultural measure is to bring the tree species only to sites that meet their needs and thus maximizing the probability to get healthy stands, which can fulfill all services we expect from them. This was demonstrated with the example of the demands on soil properties of beech, ash and sycamore from 806 observation plots in Switzerland [51]. The study revealed that ash and sycamore are much more sensitive to soil characteristics than beech. "Shortage of nutrients limited the distribution of ash and sycamore and excess of toxic elements the distribution of ash”. The authors concluded: “It is not advisable to plant ash or sycamore or to promote their natural regeneration beyond the critical values for soil acidity and nitrogen supply. A sound knowledge of the soil properties required by tree species is a prerequisite for addressing many practical and scientific issues such as forest management or the predictive mapping of tree species”. A large number of studies have dealt with the effects of tree species and/or the harvesting regimes on ecosystem services. A monitoring study in mixed spruce/beech stands in the Czech Republic from subsequent observation campaigns in 1972, 1996 and 2010 revealed that beech dominated on dry terrestric soils and spruce on wetter and more acidic soils [107]. The authors conclude that the “current expansion of beech is expected to continue on terrestrial soils but will probably slow down with increasing soil wetness” under climate change conditions.

The effect of the admixture of evergreen and non-evergreen oaks in pine stands on microbial activity and the mineralization intensity of organic matter were examined in Southern France [108]. The study revealed an additive effect of oak admixture enhancing mineralization intensity and mobilization of nutrients from organic matter especially in stands with evergreen oak. The authors conclude that “admixtures of oaks and pines can potentially maximize the diversity of nutrient resources and consequently favor microbial diversity, biomass and catabolic potential, through complementary ecological niches”. The dependence of mycorrhiza communities of tree species and nutrient availability was studied in Western Poland [69]. The study revealed that “Coniferous tree plots were characterized by lower pH values, plots with deciduous trees by higher concentrations of total Ca and exchangeable forms of Ca, K and Mg. Arbuscular mycorrhiza fungi abundance in soils and roots increased along with increasing soil alkalinity and macronutrient levels”. Model scenarios assuming the whole forest area would be covered with spruce vs. beech were compared in a regionalization study in SW Germany based on data from regular soil monitoring. In the topsoil, at slope shoulders, no significant difference between the spruce and beech scenarios could be detected. At lower slope positions, the base saturation of the beech scenario was 0.3–2 times higher than that of the spruce scenario [109].

The deposition of acidity and nitrogen were substantially altered by tree species and stand structures in the Black Forest (SW Germany). The deposition load was in beech-dominated stands about 45–85% lower than in spruce stands. The leaching of nitrate out of the rooting zone (120cm depth) is equal in beech-dominated stands to the deposition and is, in spruce stands, about two to three times higher. It can be stated that the change from spruce stands to beech stands has a potential to reduce the impact of further deposition on the forest soil to about half the value in spruce stands. Moreover, beech has a strong water preservation potential in that region regarding nitrate leaching [13]. Zeller et al. [110] observed in 21 Douglas stands in France unexpectedly high nitrification rates and concluded “that even under optimal conditions for tree growth (high biomass increment) an excess of nitrate remains in the soil with a peak in autumn. As nitrate is highly mobile in the soil profile, leaching loss of nitrate and cations may affect surface and groundwater quality, as well as the sustainability of soils by an acidification process”. Fleck et al. [98] suggested for the northern flatlands of Germany that the sink strength of forests for N should not be “additionally lowered by overly strong reductions of standing biomass, since they are already at the limit of their N retention capacity”.

There have been several studies suggesting silvicultural approaches to support C-sequestration. Disturbance of the crown closure through clearcuts create long-lasting leaching of dissolved organic carbon (DOC) and, thus, decreases the SOM pool [111]. SOC stocks observed in oak-dominated stands in Denmark are not driven by decreased SOM decomposability. However, lower specific carbon mineralization in the 200-year-old forest suggests that the stability of C and retention of N may increase in a longer perspective [86]. In Poland, in beech and pine stands, it was observed that, under beech, much more organic matter was accumulated in mineral horizons than in organic horizons [112] and that beech stands after the removal of pine stands accumulated over 20% more organic carbon content.

To accumulate deadwood in forests is a usual measure to enhance the habitat value of forests. Wambganss et al. [113] examined if deadwood would contribute to the formation of stable SOM and found that, on silicate bedrock, deadwood increased the free light SOM fraction by 57% compared to the reference points. In contrast, on calcareous bedrock, deadwood decreased the free light fraction by 23%. Thus, it depends obviously on the chemical status of soils if deadwood contributes to stable or labile SOM forms, and the accumulation of deadwood cannot clearly be judged as a strategy to enhance long-term C-sequestration.

Besides tree species selection, the harvesting regime and disturbance of crown closure tends to increase the leaching rates, since plant uptake and crown interception are reduced in gaps or clearcuts. Moreover, a more open stand structure provokes increased mineralization of organic matter because of higher temperatures and water availability. Papaioannou et al. [114] found in spruce stands in Northern Greece that harvesting practices generally negative impact soil N and organic matter in mineral soil, as well as the C/N ratio and exchangeable Ca. The authors observed that, after 15 years, the nutrient availability and organic C accumulation recovered to similar levels to those of the unmanaged sites. In SW Germany, it was derived from extensive ecosystem monitoring plots (Level II) that, even under the influence of high deposition loads, permanent cover or gap-oriented harvesting regimes provided valuable options for the preservation of site sustainability in terms of equal or slightly positive balances of basic cations. In the opposite, “rough silvicultural management practices” like spruce monoculture with clearcut result in high losses of basic cations at the same site [14].

4.2.2. Technical Approaches for Forest Soil Preservation

The silvicultural management options through orienting tree species selection or harvesting regimes on preservation of soil functions and ecosystem services is the main part of sustainability strategies in forest management. However, some ecosystem disturbances are so heavy and natural recovery is so slow that technical management option must be used to accelerate recovery of soil functions and thus stabilize forest ecosystems which is strongly recommended in times when new strains and stresses are fast emerging, e.g., by climate change. Deposition driven soil acidification is such a fundamental and long-lasting damage on forest soil functions. Soil protection liming is an effective counter-measure, with low side effects, against unnatural soil acidification. By comparing the acidification status between the National Forest Soil Inventories of 1994 and 2008 in Germany it could be shown that on limed monitoring plots the base saturation increased by 88% more than on not limed plots [115]. Therefore, the authors conclude that “forest liming of soils with considerable acidification is furthermore recommended to balance negative impacts on soil functioning, the vitality, and growth of forests”. A large-scale forest liming trial which was undertaken in SW Germany since 1983 represents with repeated liming after 20 years the liming intensity of a practical soil protective liming program. Natural recovery on the control plots in soil pH was in the time span 2003–2015, on average limited to an increase of 0.2–0.4 pH units in the forest floor and 0.1–0.3 pH units in the mineral soil. Exchangeable cations calcium and magnesium slightly increased also at the control plots, although the base saturation remained <20%. Lime treatment greatly accelerated the rise in pH by 1.2–1.3 units and base saturation by 40–70% in the organic layer, as well as 0.3–1.2 pH units and base saturation by 7–50% in mineral soil [116]. The authors conclude: “Liming of acidified forest soils significantly adds to natural recovery and therefore helps to establish greater buffering capacities and stabilize forest nutrition for the future”. Berger et al. [117] found in beech stands in Austria that “the beech trees showed no sign of recovery from acidification although S deposition levels decreased”. It is expected on the long-run that liming would lead to better exploitation of the potential rooting zone because of more favorable chemical and physical properties for root growth in the mineral soil. Thus, water and nutrient supply of tree should be enhanced. Kohler et al. [118] examined whether this would lead to an enhanced resistance, recovery or resilience of the growth rate of

Spruce against drought events. They found that "recovery and resilience of radial growth after severe drought events were generally better in spruce trees of limed treatments. This indicates a shorter stress period in spruce trees growing on limed soil, which may reduce their susceptibility to secondary, drought-related pests and pathogens".

If heavy forest machines are moving upon unprotected forest soils their deformation and compaction is inevitable. Therefore, the most effective strategy to minimize these damages is to establish soil preservation guidelines which restricts machine traffic to regular skidding trail systems with prescribed distances of the skid trails ranging from 20 to 40 m. Any wheeling of heavy machines between these more or less parallel tracks should be forbidden. Such guidelines already exist in most regions of Germany.

In order to focus counter strategies on sensitive sites, it would be helpful to know sites being tolerant against soil deformation. However, this differentiation, e.g., according to soil texture is difficult, because apparently, less susceptible textures like sand [11] or peat [119] also get damaged.

Technical measures like wide, low inflation tires or brush mats can alleviate the problem but generate no security because of a high uncertainty resulting from high variation of soil properties and dynamic machine impacts. A LIDAR–based study on rutting in skid trails revealed that low tire pressure may mitigate the impact of forwarders on soil deformation and the greater the number of passes, the greater the degree of soil disturbance [120]. Green et al. [121] could show that cable assisted, tethered harvesters and forwarders lowered the spatial distribution of machine influence on compaction.

The main problem of soil deformation and soil compaction is that natural recovery time is in any case very long. A controlled compaction trial on fine grained hydromorphic soils in France showed after seven years no sign of recovery [122]. In SW Germany skid trails of regular harvest operations with time delays up to 24 years between tracking and examination were investigated in order to characterize the status of recovery of essential soil functions. Gas diffusion coefficients and the fine root distributions of comparable sensitive silty loams were used to describe the disturbance of soil functions still detectable after decades. Up to 14 years after machine impact, gas diffusion coefficients and root densities in the upper mineral soil under wheel tracks showed no signs of restoration. In the subsoil, 24 years after machine impact, significantly reduced root densities occurred [94]. Therefore, a need of effective and not too cost-intensive measures for an active acceleration of soil deformation and their ecological effects is given. This applies especially for skid trails which should be abandoned because of technical reasons or in the case of irregular machine impact, e.g., when after windthrow regular skid trail systems are destroyed or not any more detectable. In a controlled wheeling experiment in SW Germany the recovery of soil structure on compacted skid trails, which had been treated with a combination of regeneration techniques (mulching, liming, planting alder trees or a combination of them) has been monitored. After four years, higher values of the diffusive gas permeability and macropores indicated significant improvement of soil aeration in the topsoil. In the topsoil, root density increased with increasing soil gas permeability, while in the deeper horizons only few macropores are occupied by fine roots [123]. The combination of technical treatments and planting of alder trees improves the circulation of air and water through the pore system. This leads to decreased CO_2 concentrations and increased root growth. Both are indicative of an initial recovery of soil structure. The planting of root-active trees showed a substantial regeneration effect. The root growth rate (cm cm^{-2}) in the mulched and planted variant approached after 4 years observation the range of the undisturbed control [124].

4.3. Conclusions

This literature review revealed that forest soils provide a predominantly differentiated soil structure being the basis for their high ecological functionality. Thus, forest soils are the favorable basis for manifold ecosystem services as FAO stated [27,28]. Since conventional soil descriptions provide only indicator variables and boundary conditions for soil functions and not data on the functions themselves, they have to be assessed from soil descriptions by means of so called pedotransfer functions (PTF) [125,126].

The literature cited in Section 3.1 support the conclusion that parameters like aggregate structure and connectivity of the soil pore system are crucial for soil functions. These parameters are not part of the conventional content of soil descriptions, e.g., of the World Reference Base [127] and can without additional and time-consuming measurements only indirectly and with high error probability been assessed by means of PTFs. Rabot et al. [128] suggested to derive information on aggregate structure and pore continuity by means of image processing techniques which is in line with the results discussed in Section 3.1.1 in this study. These approaches suggest that further research on quantification of the secondary soil structure is needed as a basis for modeling of soil functions like, e.g., water infiltration, plant available water storage, soil aeration and nutrient transport with the seepage water.

Ulrich stated that: “Forest ecosystems are characterized by a hierarchy of processes, differentiated according to spatial and temporal scales” [24,25]. Thus, natural forest ecosystems are in their natural status well buffered against external disturbance which can deflect them on the short run, but small scaled processes like, e.g., chemical acid-buffering reactions can soon bring them back to their specific attractor space. However, if the change of environmental conditions is too fast and too strong and thus over-ride the small-scaled buffering mechanisms, the signals of the disturbance reach the medium to large scale like die-back of the rooting system as reaction on deposition-driven soil acidification or by soil compaction through heavy forest machinery.

If forest management should optimize multi-functionality in a sustainable way, it must be based on “in-depth knowledge related to ecosystem processes and functions and soil state variables” [29]. Since scientists provide detailed quantitative information about soil functions but tend to “overlook practical, site-specific implications” which are common to practitioners [29], close cooperation between soil scientists and forest management practitioners seems to be the key to enable a holistic management approach comprising the relevant process scales up to the macro-scale where forest management takes place. Crucial precondition for the reliable transfer of point-related measuring data from environmental networks or scientific projects to the landscape level, are multivariate regionalization models which assess environmental and/or soil data on the whole forested area of landscapes with reliable error identification. “Base saturation could for example be predicted with an accuracy of 50–70% (in terms of the multiple R^2) using topographic variables, geologic substrate, stand characteristics and information about forest liming as predictor variables in multiple linear regression analyses. Thus, regionalization models achieve the role of decision support tools for planning of forest management at the landscape level” [109].

It is evident that active management measures must be set in action to preserve the vulnerable functional structures of forest soils under the actual fast changing environmental conditions. Doing so, always the complexity of physical, chemical and biologic agents contributing to build-up and sustain these prodigious structures has to be considered. Without keeping soil reaction in the range of living conditions of mycorrhiza and microbes, sufficient soil aeration for optimal root growth and planting tree species tolerating the expected climate conditions, the preservation of forest soil functions and forest ecosystem services, as we know them from experience, will fail.

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Appendix A

Table A1. Regional and climatic context of the 128 articles cited. Climate zones according to Reference [26].

Regional Context	Climate Zone Köppen-Geiger	Titles Cited	Titles	%
World wide	all except EF, ET, BW	[20,26–28,48,87,125,127,128]	9	7.0
Europe wide	Dfa, Dfb, Dfc, Cfa, Cfb, Csa, Csb, BSk	[8,15,17,21,31,47,49,70,76,97, 103,106]	12	9.4
N-America, Canada, subpolar, no dry season	Dfa, Dfb, **Dfc**	[71,73,121]	3	2.3
Scandinavia, subpolar, no dry season	Dfa, Dfb, **Dfc**	[36,72,104,119,120]	5	3.9
Scandinavia, cold, no dry season	**Dfb**, Dfc	[3]	1	0.8
Europe, cold, no dry season	Cfa, Cfb, Dfa, **Dfb**, Dfc	[1,2,4,5,22,24,25,34,35,43,46, 51,61,62,64,69,77,84,86,90,92, 101,105,107,111,112,117]	27	21.1
Europe, temperate humid	Cfa, **Cfb**, Csb	[6,9–14,16,18,19,23,29,30,37, 38,42,44,45,50,52–58,63,75,82,83,85,89,93–96,98,100,109,110,113,115, 116,118,122–124,126]	48	37.5
Asia, N-America temperate humid	**Cfa**, Csb, Dfc	[60,88,91]	3	2.3
Europe, semi arid	BSk, **Csa**, Csb, Cfa	[32,33,65–68,81,102,108,114]	10	7.8
Asia, Africa, semi arid	**Bwk**, Cwa, Cfa	[7,74,79,80]	4	3.1
Asia, Africa, S-America tropic	**Af**, **Am**, As, Aw, Cfa	[39–41,59,78,99]	6	4.7

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