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Chapter

Forest Soil Water in Landscape Context

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Abstract

Forests play an irreplaceable role in linking the water cycle with the functions of soil. Soil water not only enhances the stability of forests, but also its run-off and evaporation affects the growth of plants in different ecosystems. The forest soil water balance is contextualized within the immediate and more global landscapes, in terms of relations of water to the soil environment and bedrock, participation in the local water cycle within a catchment basin and in the global cycle between ecosystems. Modifications by human civilization can have significant impacts, including erosion intensification, eutrophication, salinization, spreading of single-species plantations, and regime shifts. Forests regulate the movement of water in the soil environment by reducing the intensity of run-off. Such moderated run-off prevents the occurrence of flash floods, maintaining continuous availability of water for plant and human use. Participation of soil water in the cycling of elements in forests is modified by soil organic matter balance. The preservation of hydric functions in forest soils depends on prioritization of water balance restoration in every catchment basin enclosing the local element cycle. More fundamentally, the development of a synergistically interlinked system, centered around the soil-forest-water-civilization nexus, must become an urgent priority.

Keywords: water potential, available water capacity, forest soil hydric potential, soil water communication, soil water and human society

1. Introduction

In this book section, we deal with four mutually coherent sub-sections which, according to the author teams should present the topic progressively from base soil-water interactions, properties and parameters on general level (Section 2.1); landscape and forest-horizontal water relations (Section 2.2); landscape and forest-vertical water relations (Section 2.3) and holistic soil-water-forest-landscape-civilization nexus (Section 2.4).

Soil water refers to any water contained in the soil in liquid, gaseous and solid states. From a forestry point of view, water can be considered as a key factor of production and its sustainability, while also contributing to the stability of the forest ecosystem, since water is essential, not only for nutrition (both as a reaction medium and as a substrate), but also for the growth and development of stands. Soil water in the liquid state acts by its deflocculating, dissolving, hydrolytic and translocation effects. Soil water is irreplaceable in a wide range of Physico-chemical, biochemical and biological processes and de facto it conditions soil formation and the development of the pedosphere. Oxygen, upon which all anaerobic life depends, is generated from the water-splitting reaction. Entire photosynthetic physiological pathways, such as Crassulacean Acid Metabolism (CAM), are engineered around water conservation.

2. Soil water and its relation to the soil environment

2.1 General characteristics of soil water

Water exists as a soil solution in the soil [1]. Gases (O_2, CO_2, NH_3, N-oxides, S-oxides, etc.) and minerals are dissolved in this solution. Dissolved mineral substances originate from weathering processes, where they are released from rocks into the soil solution, and also from the above-ground part of forest stands, either by means of emission or percolation through tree crowns. Up to 50–250 kg of minerals per hectare a year penetrate the soil by so-called 'cloud/fog water' [2, 3]. This results in a significant enrichment of the soil surface not only in the form of plant litter but also through rainwater, including such elements as Ca, Mg, K, P and N. These elements react in the solid phase in the soil, further dissolving or precipitating. The water composition depends on the dissolution of minerals and organic compounds, on the ion exchange between the soil sorption complex and the soil solution and on the interaction of the soil solution, fine roots and soil microorganisms. Mineral (acids, bases, salts) and organic substances (colloids of dissolved compounds, saccharides, fulvic acids and amino acids, expressed as dissolved organic carbon (DOC)) are dissolved in water and then pass through the biosphere, while being regulated by climatic factors. Due to climate change and associated substantial changes in forest stand structure and functioning, the cycles and flows also change, not only at the level of soil water percolation and content but also within bulk deposition and through fall, both representing substantial sources of DOC [4].

2.1.1 Water sources and losses in forest soils

The soil water content and its availability are the results of a water balance arising from the inputs and outputs of the water cycle within the particular ecosystem [5, 6]. The actual soil moisture enters and leaves the water balance at the beginning and the end of the investigation period respectively. Individual components of the water balance [7] are subject to external influences (generally climate and topography) and internal influences (including properties, composition of the soil body and vegetation characteristics).

The most important water source is vertical precipitation in most areas of the temperate climatic zone. Horizontal precipitation is also regarded as a significant source, for example cloud/fog water in misty forests of tropical or mountain areas, dew, interception, condensation of water vapor in soil pores (especially in soils with a high proportion of macropores), capillary lift and lateral water. The water loss from the soil is primarily due to infiltration, surface run-off and evapotranspiration. Run-off is significantly regulated by forest stands, both in a precipitation-rich period (run-off is lower compared to the non-forested soil) and in a drought (run-off is higher in comparison with the non-forested soil).

The character of surface run-off and water flow through the soil depends on many factors, notably the slope gradient, the amount and intensity of precipitation, soil permeability, the depth of freezing and vegetation coverage. An excessively dried soil surface may be characterized by poor wettability, while humus acts like a permeable filter with high hydraulic conductivity after being soaked in water. This leads to less vulnerability in forest ecosystems compared with different vegetation types [8, 9]. Humus may also be characterized by lower water loss (higher retention) compared to mineral soil. The forest floor, which is typical for forest soils [10], plays a crucial and indispensable role in terms of nutrient supply [11] but also for the water regime [12]: it absorbs several times more water than mineral horizons located below and, at the same time, it reduces soil water losses.

The forestry-pedology nexus represents perhaps the greatest existential threat to humanity at present, requiring urgent action yet currently being ignored by the international community. Historical precedent is all too clear, yet we ignore this growing crisis at our peril. Deficiency of physiological water [13–15] and the potential risk of stress associated with water unavailability to plants [16, 17], both of which differ between vegetation types [18], cannot be overemphasized [19, 20]. The internal factors impacting water availability in the soil environment include the grain-size composition of the soil (the distinction of stoniness and fine earth in a differentiated way in sand, silt and clay fractions), the organic matter form and content and the thickness of soil horizons, affecting both the multidirectional water flow and the physiological depth of root distribution. Other factors include soil chemistry (increased hygroscopicity of salinated soils) [21], the degree of rooting (water drainage alongside the roots) [22] and the distribution and representation of soil pores of specific sizes, but also anthropogenic impacts, such as pedocompaction.

2.1.2 Soil water content, forms and water regime

One measure of increase and loss of water in the soil is the instantaneous soil moisture, represented by the total sum of water sources and losses and the water retention capacity. It is expressed in percentages by volume (Θ) or the mass (w) water content and also mm of water supplied, depending on different applications. In particular, forest soil humus horizons, act differently depending on stand species composition [23], the indicator of volumetric water content is more appropriate than the mass water content. The reason (also associated with low humus bulk density) is a significant disproportion in volumetric and mass water content when the maximum volumetric water content is always less than 100% while the maximum mass water content can be far more than 100% (even exceeding 1000%).

Water is bound to the soil by the range of forces [24, 25] (chemical, physico-chemical, physical and biological). The components that, together, produce water potential (see below) act simultaneously to influence water behavior and water content in the soil. There is no sharp boundary between these different forces. As a rule, the water-binding forces in the soil overlap and they are frequently related to specific soil horizons. The resultant sums of forces that hold water in the soil (matrix, osmotic, sorption, capillary, pneumatic, gravitational forces) together make up the soil water potential (Ψ) representing the strength by which soil water is bound. It can be said that it represents energy (work) that we would have to expend to 'drain out' water from the soil. The negative pressure is then referred to as suction or tension; hence it is expressed as the negative value of the atmospheric pressure [−Pa, −kPa, −MPa], where 0.1 MPa = 1 bar = 1020 cm of the water column = 760 mm Hg = 1 atm.

The soil water potential can also be formulated in pF curves, where $pF = -\log \Psi$. The pF curves thus express the relationship between the soil water content and the soil water potential (**Figure 1**).

Water flow in the soil is conditioned by means of two processes [27, 28]: infiltration (determined by field or laboratory infiltration tests), where empty pores are filled with soaked water, and unsaturated flow. This sort of flow gradually slows down until all the pores are filled with water and water flows freely through non-capillary pores. Thus, the soil is fully saturated with water, and saturated flow is realized. This is not uniform, but, rather, tongue-like in terms of the water column, which gradually increases from the soil surface to greater depths.

In sloping landscapes of humid areas, lateral water is also added to rainwater [29]. This means that as we descend a sloping landscape, more water flows on the slope lower down the incline than higher up because soil water from the higher slopes is added to infiltrating rainwater. This phenomenon may also contribute to the differentiation of the soil types over a short distance.

As can be seen from the characteristics of the water potential, water flow in the soil is influenced by moisture gradients, but also by temperature and the mineralogical composition of the soil. The downward direction of water percolation typifies humid areas, where this type of movement contributes to the eluviations of soil particles. Under arid or semi-arid climate conditions, prevailing water flow is upward, as a consequence of suction pressure, and thus water rises by capillary action through the soil profile.

The moisture regime represents the distribution and movement of water in spatial and temporal terms [30]. It incorporates water inputs into the soil, water retention in the soil and water leakage from the soil. The water regime is conditioned by climate, vegetation, the soil-forming substrate, the groundwater location, the terrain relief and the landscape history. The water regime is generally expressed in terms of the relationships among temperature, potential evapotranspiration, precipitation and actual evapotranspiration. The soil water regime can be classified into several categories: aquic, udic, perudic, ustic, aridic and xeric [30]. Based on the resulting balance, there is a water deficit (percolates into underground layers) or a water surplus (retained in the soil).

2.1.3 Soil hydrolimits and plant-available water

Soil hydrolimits (**Figure 1**) represent the strength of water binding in the soil [7, 26, 31, 32]. They denote qualitative and quantitative alterations in soil-water relations, or how strongly water is retained in the soil (in what volume) at the given soil moisture level. Soil hydrolimits are soil moisture values achieved under well-defined conditions and they describe the relation of water and soil according to the flow of water in the soil and its accessibility to plants.

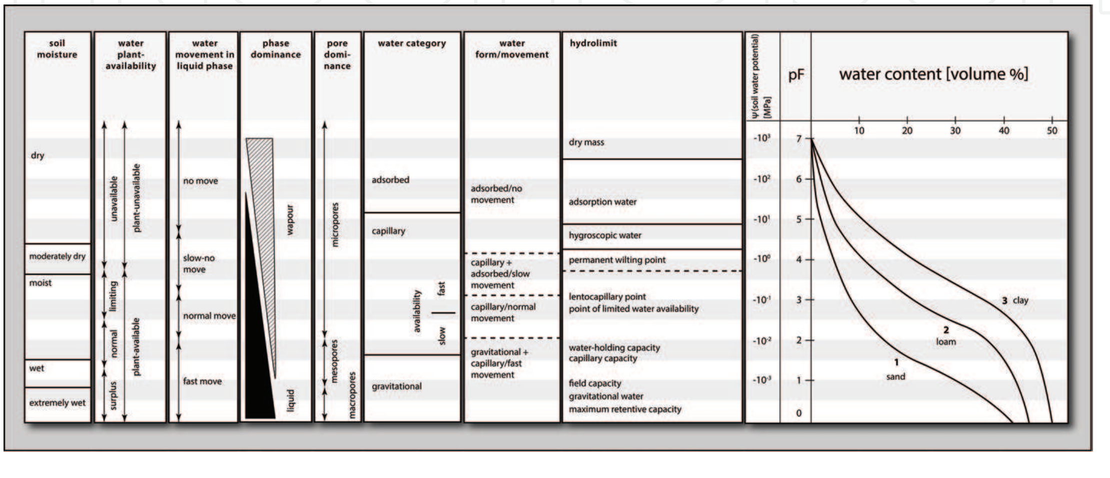

Figure 1.
Relationships between various forms of water and binding forces in the soil (modified according to Vavříček, Kučera [26]).

The significant hydrolimits are:

- Maximum retentive capacity: soil fully saturated with water achieves a hydrolimit, which corresponds to the soil porosity

- Gravitational water: Ψ = −33 to −10 kPa or more; under natural conditions, its presence in the soil is qualified mainly by precipitation. The direction of the gravitational water flow is in the direction of gravity to the lower soil strata

- Maximum capillary capacity: volume of capillary and partly semi-capillary pores. Suction forces at this level of the soil water content are in the range of pF 1.6–2.0 (Ψ = −0.01 to −0.007 MPa). Only coarse pores are present at this saturation degree without water

- Water-holding capacity (WHC): corresponds to the pF curves in the interval of pF = 2.0–2.7 (Ψ = −0.08 to −0.01 MPa), expressing the ability of soil to retain a certain amount of water for a longer period (24 hours). We can ascertain the division of soil pores into capillary and semi-capillary pores by identifying the water-holding capacity

- Point of limited availability: the initial phase of the deteriorated availability of water and its soil mobility. Water still flows continuously through the soil, but merely in the thinnest pores. The water flow is interrupted in semi-capillary and non-capillary pores and water only encapsulates the soil particles

- Lentocapillary point: occurs at pF = 3.0–3.3 (Ψ = −0.3 to −0.1 MPa). It is the soil moisture, which is in the range between slightly and scarcely mobile capillary water. It corresponds with a state where a sudden drop in mobility begins by interrupting capillary water

- Wilting point: starts at pF = 4.18 (Ψ = −2 to −1 MPa; conventionally −1.5 MPa). It indicates the soil moisture level at which plants are insufficiently supplied with water

- Pellicular water: at pF = 2.1–4.0 (−5.0 to −0.1 MPa). Water encapsulates soil particles in a thicker layer, not moving with gravity, but merely from particles with a larger pellicle to particles with a smaller one. It is unavailable to plants; sometimes it is perceived as hygroscopic water

- Hygroscopic water: is bound to the soil by means of adsorption and osmotic forces. As a rule, it only encapsulates soil particles, and Ψ is generally less than −3.1 MPa, and so it is immobile and unavailable to plants

- Field capacity: represents the ability of the soil to retain the maximum amount of water in the natural profile (in site conditions) against the effects of the Earth's gravity, that is without further active water removal, for a longer period of time (24 hours). This hydrolimit, which is de facto compatible with the water-holding capacity, is widespread, especially in agronomic soil science, where it is also detected by field methods

Plant-available water capacity (PWC) reflects the increase and loss of water in the soil. It is expressed in %, but also in mm of supply [25, 33]. The determination is based on the assumption that a column of water of 1 mm in height represents a water volume of 1 l per 1 m^2. For the practical application of this relation, it is essential that volumetric percentages of the ascertained soil moisture content, or the given hydrolimit, express the soil water supply in mm for a soil layer of 100 mm. In forest soils, this value is depicted in terms of the root distribution for the upper 20 cm of soil, and the observed volumetric % of the soil moisture is therefore multiplied by two to express the value of the plant-available water capacity. The plant-available water capacity formulates the height of the water column of the soil within the range of the wilting point and the water-holding capacity. Thus, PWC represents the condition of the soil moisture where soil water is bound for a relatively long time, but it is still available to plants. The highest values of the plant-available water capacity are in loamy soil. Lower values exist in clay soils, and the lowest values are found in sandy soils [24, 34]. In addition to the texture characteristics, it is necessary to take into account the degree of soil stoniness, which practically does not participate in water retention and represents an inactive soil component in terms of water retention capacity, when determining the plant-available water capacity. PWC also expresses how much torrential rainfall the soil is capable of collecting. From this standpoint, it is an important indication of the water-retaining capacity of the landscape of which the soil is a part as a geological formation, which, with great efficiency, counteracts the flood distribution caused by torrential as well as prolonged rainfall. In this respect, soil, especially forest soils, with several times higher PWC in comparison with agricultural land and much higher than urbanized areas, plays an irreplaceable role in water management in the landscape.

Another soil property, soil moisture storage, relates directly to the actual soil water status, and shares the same units and the same principles as PWC. It can be expressed as the variance between the current soil moisture and the wilting point in mm, representing the current content of physiologically available water.

2.1.4 Soil porosity and capillarity

Apart from the soil structure, porosity is a major factor in the spatial arrangement of the soil and is fundamentally involved in the characterization of water and soil-air regimes, and in the soil–plant (forest stand) relationship. Pores exist in the soil both between soil particles and structural elements (aggregates). If the porosity value between aggregates is marked with the symbol A and the porosity value within the aggregates with the symbol B, the optimum soil porosity may be expressed as A:B = 1:2.

Water is bound most weakly in non-capillary and semi-capillary pores. This kind of water is called gravitational water. Non-capillary porosity occupies pores with very low water retention capacity, in which water moves under the influence of gravity. This is also why the term gravitational water is used for water contained in non-capillary pores. When non-capillary pores dominate, the soil has a low available water content due to its rapid flow to depths unavailable to plant roots.

Capillary water is present only in capillary pores. It is not tied to the Earth's gravity and can move in all directions in the soil. Capillary water is bound thanks to capillary adhesion and the surface tension of menisci. The optimal proportion of capillary pores is approximately two-thirds of total porosity [35–37]. An excess of capillary pores complicates infiltration of water, and it also inflicts an elevation in surface run-off, increasing the risk of erosion. A lack of capillary pores prefigures low plant water supply, low water retention capacity and low water absorption.

Water can rise above a continuous groundwater table by means of capillaries. This is called capillary rise [24, 25, 38]. The capillary rise is approximately the same as the soil particle size (pore diameter = 0.3–0.7 times the soil particle diameter). The capillary rise varies from 10 of centimeters to metres within a given year.

The volume relation of capillary and non-capillary pores is expressed by the minimum aeration capacity [26, 39]. This represents the volume of air-filled pores when the soil has reached maximum capillary capacity. The lower limit value of the minimum aeration capacity of forest soils can be considered to be 8% vol, while the average value (e.g. for topsoil in forest nurseries) is 10% vol. If the soil is excessively aerated, the soil is easier to heat, vapourization increases and soils are contrarily dehydrated. Therefore, a value above 20% can be considered an upper but still acceptable limit, with a risk value of 25%.

2.2 Hydric functions of forest soils

2.2.1 Effect of climate change on forest water cycle

A global (large) water cycle can be defined as a water cycle in which water is transferred between the land and oceans and a local (small) water cycle is defined as a displacement merely over oceans or drainless areas of the land. The water cycle governs all of the natural forest functions. However, forest ecology represents an important aspect of the hydrological cycle at the planetary level, and so these effects impact at a global level. Whereas the global water cycle is related to the adaptation of forests to climate change, the local water cycle interlinks mutual interactions between related forest complexes within the catchment. In general, the impact of forests on global climate change is at its most significant due to cloud formation in the tropics. The formed clouds reflect solar radiation more effectively and, therefore, cool the atmosphere more than does the absorption of greenhouse gases by vegetation [40]. Environmental pollution, deforestation and transformation of the tree species composition reduce the natural ability of forests to adapt to climate change. Monitoring of soil properties focused on water and nutrient cycles in different forest ecosystems offers a tool for assessing the impacts of climate change [41].

Forest functions are the outcome of the interactions between the environmental, soil and vegetation subsystems. Natural functions are based on processes that support self-organization, recovery and development of the ecosystem. The interrelated processes of biodiversity, organic matter formation and nutrient cycles promote production, air circulation, (in-)filtration, evapotranspiration and site differentiation [42]. The water cycle controls the carbon cycle through which forests modify local cycling of all nutrients. The parts of the water and carbon cycles within soils have linked individual forest functions to the self-organized ecosystem [43]. The degree of interconnection is subject to the flow of soil water, but simultaneously also by its scope in the specific cycle.

The global effect of forest functionality consists in the transfer of evaporated water through cloudiness within the catchments from the areas with more significant vapor in the lower parts than the areas in the upper parts, where cloudiness condenses into more frequent precipitation. Precipitation in the upper parts of the catchments flows to the lower parts, where additional water complements the higher evaporation and lower precipitation [44]. As temperatures rise, this phenomenon is intensified: evaporation elevates, and drought deepens in drier areas, while precipitation in wetter areas increases. The consequent accentuation in disparities between drier and wetter areas disrupts the interconnection of forest functions among vegetation zones [45].

Even though the local water cycle defines the hydric functions of forests to catchments, their response to climate change depends on the interconnected monitoring of variability not only within the catchment but also among remote catchments. The link between the effects of global and local water cycles also exposes mutually unrelated forests to reduced water availability and consequently to reduced service provision [46].

2.2.2 Effects of nutrient cycles on forest hydric functions

The forest promotes both water and carbon cycles in parallel because they are related to energy flows in the ecosystem. While natural plant-to-plant feedbacks between plants and nutrient cycles underpin ecosystem functionality, forest damage disrupts these processes. If forest damage results in the disruption of the carbon cycle, at the same time the local water cycle is also disrupted, followed by negative impacts on the functioning of related ecosystems [47]. Recognition of forest function damage through the disruption of soil properties is based on the determination of critical values of physical and chemical properties involved in the processes of formation of individual ecosystem functions.

Carbon enters the ecosystem in the form of atmospheric CO_2 through photosynthesis of plants, in which solar energy for the synthesis of organic compounds in cells is transformed by the decomposition of water. Plants release carbon by respiration, by being consumed by herbivores or fungi and by exchange reactions with soil biota and litter. The most significant conversions of organically bound carbon occur in the soil. Plants mediate carbon into the soil both by litter to the surface and also by root necrosis, exudation, root cap sloughing or exchange with microorganisms within the soil body (e.g. through mycorrhizal sheaths). Litter is mechanically or biochemically decomposed into residual chains at pH ˃ 4.5, or into stable polyphenol nuclei at lower pH, as a result of the tetravalency of carbon covalent bonds. Soil organisms or enzymes are capable of decomposing chains into organic acids under favorable conditions, but the prevailing unfavorable conditions allow merely incomplete decomposition. Soil carbon accumulates as a consequence of the imperfection of decomposition [48]. However, destruents mineralize organic residues back to CO_2 under a range of unfavorable conditions (**Figure 2**).

Carbon compounds significantly attract soil water through adhesion to organic molecular chains. That is why carbon storage in the soil irreplaceably increases the WHC of the entire ecosystem. Subsequently, the detection of forest functions using intra-soil processes focuses on common inputs or outputs of substances and energy in the soil subsystem. This can be done by ascertaining the length of the delay of the forest stand response in the aftermath of the alteration of soil property values [49]. The evaluation of conditions of substance inputs or outputs concentrate on assessments of whether or not biochemical and physical properties can regulate the processes of water or carbon cycles. Even though the selected soil properties correlate with one another, the temporal variability of physical properties is incomparably longer than the significant seasonal variability of biochemical properties. Whereas the variability of (bio)chemical properties indicates a threat to the forest after an episode of drought or extreme daily precipitation sum (EDSP), an alteration to correlations of the forest status with poorly variable soil physical properties indicates deviations in development during environmental change [50].

The selection of intra-soil processes affecting forest functions is based on the study of the variability of properties in different parts of the soil body. The functions of circulation, infiltration, evapotranspiration and differentiation are typically regulated by means of one soil process. The indication of individual forest ecosystem functions at the soil level (**Table 1**) can be derived from the generalization of studies focused on the relation between the growth conditions with water balance, biodiversity and the health status of forests [49, 51–53].

Table 1 shows the soil properties involved in water and carbon cycle processes that increase the efficiency of individual forest functions. The production

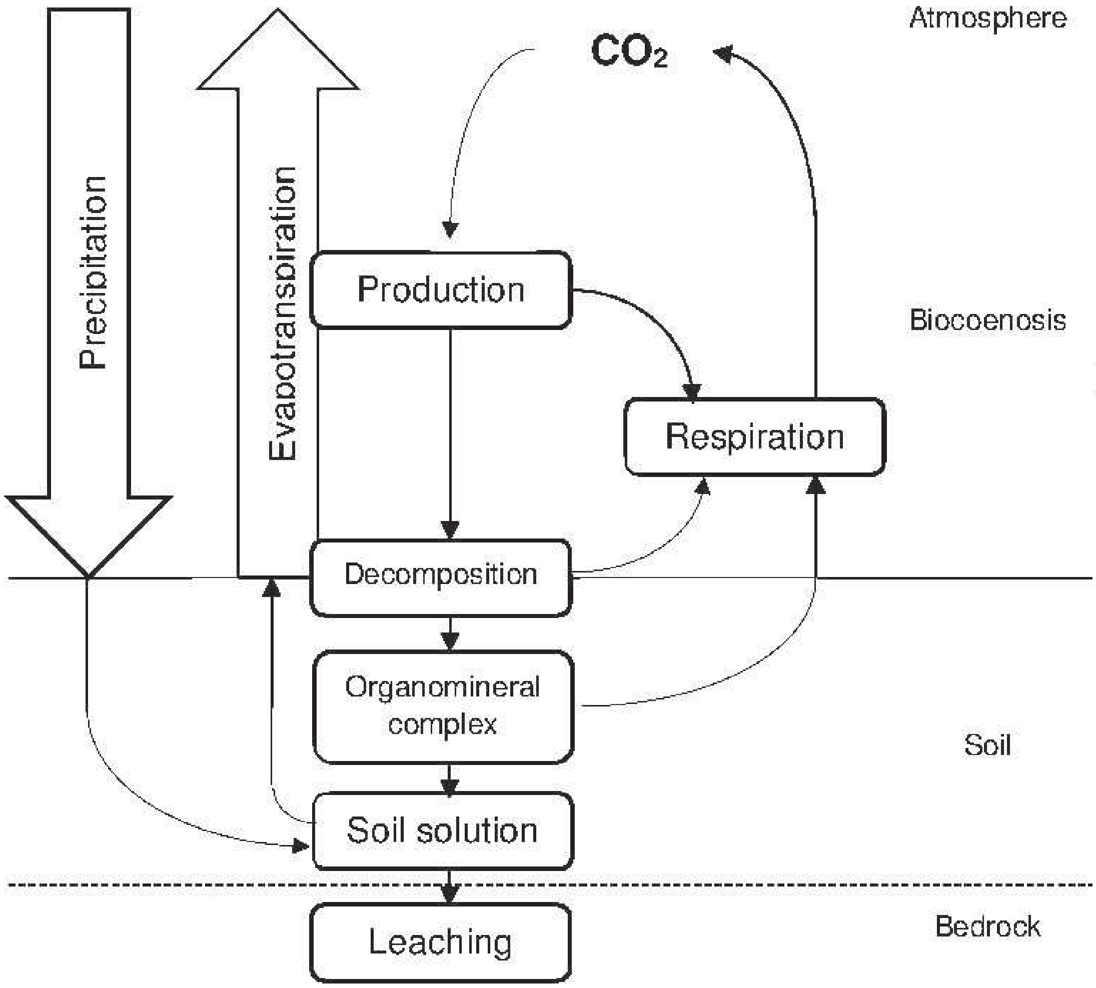

Figure 2.
Connectivity between cycles of water (left) and carbon (right) in forest ecosystem forming hydric functions.

Forest function	Hydric process	Indicative soil property
Production	Photochemical water disintegration	Catalase activity
Air circulation	Vapor pressure decrease	Minimum aeration capacity
(In-)filtration	Physical sorption	Organomineral complex content
Evapotranspiration	Evaporation	Soil water potential
Differentiation	Debasification	Soil water acidity

Table 1.
Relationships between forest functions and water cycle processes indicated by the selected soil properties.

indication is centred on the catalase activity, which depends on the intensity of aerobic metabolism. The correlation of the soil catalase activity with the content and character of organic acids reflects the variety of humus forms. It is naturally associated with differentiated forest cover. If the forest disruption does not damage the humus diversity, the catalase activity remains stable. Air circulation is dependent on the atmospheric flow reducing vapor pressure above the partial surface that the soil maintains thanks to minimum aeration capacity. Infiltration is also conditioned by organic matter and clay minerals, which may form organomineral complexes. They significantly retain water by adhesion and capillary rise in capillary pores remaining among their particles [54]. On the contrary, evapotranspiration is the sum of evaporation from the individual types of surfaces in the ecosystem. The rate of evaporation from the soil is directly proportional to the soil water potential [55].

In contrast, the capability of ecosystem differentiation is estimated by the chemical composition of the soil solution. It grows when soil run-off contains a minimum of base cations. Increased concentrations of bases in run-off water indicate soil acidification, which reduces the ecological diversity of the catchment [56].

2.2.3 Hydrographical division of forests

The soil indicators relating to forest functionality are naturally subdivided into a total of eight biomes relating to differences in water availability due to variations in evapotranspiration and the water-holding capacity (**Table 2**) [57]. Despite the differences between forest biomes, large catchments possess similar zonality of hydric functions internally. Nonetheless, the WHC affects the variances in forest hydric functions of forests between individual habitats within the catchment as its value is directly proportional to the soil types present. The largest overlaps in the WHC values occur in the catchments of Mediterranean, temperate and tropical coniferous forests with more similar soil development at medium temperature intervals relative to boreal, mangrove or tropical broadleaved rainforests [58]. For example, the values of the WHC in **Table 2** were found to be related to the macroclimatic properties of forest biomes. This can be further related to the weighted means of the soil types as found in the Harmonized World Soil Database (HWSD) [59].

Transitions of forest hydric functions in the catchment are the basis for the derivation of hydrographic zonality. Large forest catchments include montane, submontane and floodplain forest ecosystems [50]. These zones emerge thanks to the local water cycle from wetter mountains to drier floodplains. Undisturbed forests are capable of water supply to all the parts of the catchment continuously even though most water supplies on the mainlands are unavailable to plants. Over 62.4% of mainland water supplies are concentrated in glaciers, 36.2% in underground reservoirs and 0.42% in lakes or ground level reservoirs. Only 0.29% of water is found in the soil and 0.09% in rivers [60, 61]. Atmospheric precipitation over the dry land brings merely 0.008% of the global water balance, but over 50% of precipitation occurs in montane areas. Continuous water management in the catchment is ensured by forests by means of modifications of evapotranspiration and run-off. Forests cover 39.7% of the dry land

Forest biome	AP	*T*	*P*	AET	PET	WHC
Tropical rain broadleaved	33.46	21.82 ± 1.35	1988 ± 83	892 ± 200	1270 ± 172	24.96 ± 3.38
Tropical dry broadleaved	5.09	24.16 ± 1.93	1263 ± 79	717 ± 180	1203 ± 174	26.34 ± 5.09
Tropical coniferous	1.20	19.40 ± 2.31	1438 ± 83	716 ± 97	1218 ± 74	33.71 ± 6.97
Temperate mixed	21.71	9.73 ± 7.39	1072 ± 30	508 ± 127	688 ± 112	31.13 ± 9.80
Temperate coniferous	6.91	6.39 ± 7.82	918 ± 36	428 ± 88	700 ± 100	29.63 ± 8.31
Boreal	25.59	−2.54 ± 12.37	642 ± 19	256 ± 75	298 ± 64	49.11 ± 9.15
Mediterranean	5.45	15.05 ± 5.34	586 ± 26	316 ± 121	962 ± 225	32.39 ± 9.44
Mangroves	0.59	26.07 ± 1.70	1900 ± 94	502 ± 476	1303 ± 492	69.18 ± 3.89

AP, area proportion (%); T, average temperature (°C); P, annual precipitation (mm); AET, actual evapotranspiration; PET, potential evapotranspiration; WHC, water-holding capacity (%). Data according to [57].

Table 2.
Characteristics of water balance in forest biomes.

but account for 67.6% of evapotranspiration. Simultaneously, only the structure of the forest can return the evaporated water sufficiently by cloud/fog water or seasonal pollen release, which can create a condensation nucleus to form cloudiness.

Deceleration of run-off by the forest ecosystem is irreplaceable in reducing seasonal variations in water availability between winter and the growing season and in dampening of EDSP. EDSP typically exceeds the average soil WHC either in above-average climatic episodes of precipitation or during the most intense precipitation season. Overcoming WHC prefigures a temporary increase in the flow of soil water and subsequently also river water. It is precise because the values of WHC naturally alter within soil development regardless of the tree species composition or altitude, that (sub)montane forests can dampen run-off after extraordinary rainfall with similar efficiency [62]. The actual water-holding capacity of forest soils due to the constant presence of natural moisture is approximately only 30 mm, providing 22% WHC and dampening 67–75% of EDSP [63].

Alterations in the tree species composition of forests have had the greatest impact on the forest hydric functions during transitions of the seasons of the year. Coniferous trees may be characterized by average higher interception and evapotranspiration. At the same time, coniferous forests capture more snow and significantly slow down melting, reducing the surface run-off in early spring when most of the vegetation is inactive. In deciduous broadleaved forests, this deceleration of run-off does not occur due to defoliation of trees in winter and thus increased solar radiation directly impacting on the soil surface [64].

Hydrographic forest zonality indicates differentiated forest efficiency in the modification of the local water cycle. The differentiation of the effective influence of forests is determined by the relief of the landscape as well as soil development and tree species composition.

Montane forests are located in the upper parts of catchments with the highest amount of precipitation. Their structure is adapted to the application of more frequent horizontal precipitation. Soils are permeable due to the prevailing mechanical weathering. The erosion on steep slopes and the nature of the soil-forming substrate cause rockiness and shallowness of soils. The water-holding capacity of montane soils is maintained by means of accumulation and the slower degradation of humus. Montane drainless depressions with accumulating humus are habitats of ombrogenic bogs in the presence of excessive rainfall. At transitions of the mantle rock with the outcrop of impermeable subsoil, there are water springs at the points of concentrated groundwater run-off. Montane forests not only increase the total amount of precipitation but at the same time, they are crucial for stable surface water run-off. The total amount of precipitation increases not only by collecting horizontal precipitation but also by lower evaporation due to lower temperatures than in the lower parts of the catchment. Humus accumulations reduce run-off on a slope that subsequently does not cause erosion.

Submontane forests form the zonal vegetation between montane and floodplain ecosystems. They occur mostly on slopes with harmonious water balance. Soils are generally moderately permeable due to a balanced proportion of stoniness and fine-grained weathered particles. The formation of bogs is excluded on dominant, slanting slopes and more favorable temperatures that intensify soil respiration prevent excessive accumulation of surface humus. Higher clay content and lower humus accumulation distinguish water retention properties of submontane soils from montane soils. Submontane forests inhibit atmospheric precipitation only up to an amount corresponding with potential evapotranspiration, while continuous run-off along the surface as well as from the soil body occurs when WHC is exceeded.

Floodplain forests occur in a flat relief formed by floods. On the one hand, floods lay terraces; on the other hand, they tear down banks. The activity of rivers increases the diversity of soil properties, mostly at interfaces with zonal sites. The functionality of floodplain forests is determined by river water and waterlogging. The duration of the flood, the variability in the height of the river level and the fluctuation of the groundwater level induce differentiation of floodplain ecosystems. Extraordinary floods most significantly alter the dynamics of their development. The function of floodplain forests varies due to the lack of precipitation for evapotranspiration, which they are able to replace thanks to floods or high groundwater levels. The long-term decline of the soil water level at high evaporation can result in the replacement of the floodplain forest with the forest-steppe [65]. Floodplain forests with optimal soil moisture and high evaporation transpire almost 80% of potential evapotranspiration. This amount contains up to 70% of groundwater and 30% of precipitation. However, the transpiration of trees is not merely inhibited by the lack of soil water, but also by the lack of air during a prolonged flood [66].

2.2.4 Vulnerability of forest hydric functions

In Central Europe, the current health status of forest stands is closely linked to the climatic situation, particularly the availability of water for woody plants. Water in forest soils is a key part of the feedback relations, both in the soil–plant direction, currently mainly as a limiting eco-factor, and in the soil-landscape direction, in terms of the landscape water regime, water retention in the landscape and prevention of flood events.

Forest functions are threatened by dieback, fragmentation and transformation of tree species composition. The loss of forests leads to a decrease in evaporation, with cloud formation also declining. The decrease in cloud formation affects the whole catchment. Although the evaporation reduction should prevent soil moisture diminution, unlike evapotranspiration, it is not regulated by means of the vegetation cover, but merely by temperature alteration. A denuded land is easier to warm up, increasing biological activity and mineralization intensity. This occurs provided that removal of the stand component does not result in (frequent) waterlogging of a site, which would be limiting to the aerobic organisms at least until the lost functionality of the subsequent stand is restored. Soil without organic matter loses both water retention capacity and fertility. The decrease in forests is most distinctive in the lower parts of the catchment, which are more accessible, mostly non-waterlogged and more hydrologically suited for agriculture. Since the occurrence of precipitation also lowers in the spring-dependent parts of catchments as the cloud formation diminishes, the subsequent decline in river levels causes a decline in water supply to tributary-dependent parts of the catchment [67].

The greatest differences in the soil water-holding capacity are found between forested and treeless catchments. Flooding in forested catchment areas occurs in the aftermath of exceeding EDSP. Conversely, treeless catchments are affected by flash floods even after precipitation ˂30 mm. The protection of the water retention capacity of the catchment consists primarily in the prevalence of unbroken stretches of forests. Young open forest stands resemble treeless zones in terms of the water balance. Only closed stands over 20 years of age reach a water balance comparable to that of adults. Even though homogeneous forest stands provide hydric functionality similar to richly structured mixed forests, richly structured forests appear more resilient to climate change. Protecting the hydric functions of forests during climate change can be achieved in the following ways:

- Promotion of the transformation of tree species composition in favor of the natural state, with a natural proportion of trees within each stand type exceeding 50%

- Favoring understorey or small-scale differentiated farming to increase age and spatial diversity

- Maintaining a closed canopy to protect the soil surface, where understorey can be mined at the restoration stage without affecting the species diversity of vegetation

- Construction of a sufficiently dense transport network to minimize machinery driving through stands, giving priority to mining technologies that do not compact the upper soil horizons

Drought stress in forest stands has been shown to reduce both transpiration and the water content in plants [68, 69]. This occurs because of the loss of assimilation apparatus, thus reducing leaf area available for transpiration, but also because of the reduced availability of nutrients, which convert to a dehydrated state in a differentiated way [70]. At higher humidity, there is more Ca^{2+} and Mg^{2+} present in the soil solution, and at the same time, K^+ is better released by mineralization processes. This is due to the size of the hydration envelope of the ions, which conditions their hydration energy for various nutrients in a differentiated way. This is necessary for the nutrient to be taken up by the plant. To hydrate diverse ions, different amounts of water molecules are needed, so potassium is absorbed at lower soil moisture than magnesium or calcium—two elements that frequently prove nutritionally deficient even though they may be at an optimal concentration in the soil.

2.3 Soil water and its relationship with groundwater

In the contemporary cultural landscape, the natural water cycle is, to a large extent, influenced (in other words, 'shortened') by vertical water movement within terrestrial systems. Consequently, communication within soil hydrological systems and the rock subsoil is impaired. The reasons will be explained in the following section.

The amount of water is distributed very unevenly in space and time on Earth. That is why there are problems with its lack in many regions. Redistribution of water in the landscape can be expressed by the fundamental elementary redistribution equation of water (this is also referred to as the balance equation [71]):

$$DP = IR + P - \Delta S - RO - ET \tag{1}$$

where DP: deep percolation; IR: irrigation; P: precipitation; RO: surface run-off; ET: evapotranspiration; ΔS: soil water storage.

On the basis of this balance equation, two basic hydrological cycles are identified: the large and small water cycles. In the water cycle (**Figure 3**), the main sources are precipitation and the surface, lateral and underground inflow in the hydrogeological collector. Water that falls on the soil surface immediately infiltrates the soil or, under conditions of insufficient infiltration capability and hydraulic conductivity, it drains or accumulates in micro-depressions of the relief (detention). Infiltrated water is redistributed in the soil body and remains below the soil surface, suspended in a capillary manner. Gravitational water then flows out of the area laterally (hypodermically) and migrates to the capillary fringe (see below), through which it percolates into an aquiferous hydrogeological collector. In relation to the vegetation, the water cycle is influenced by evapotranspiration and interception.

Soil, or more exactly the soil environment, is the main location of infiltration of water into the rocky underground environment. In general, this is the most important environment for the replenishment of groundwater supplies.

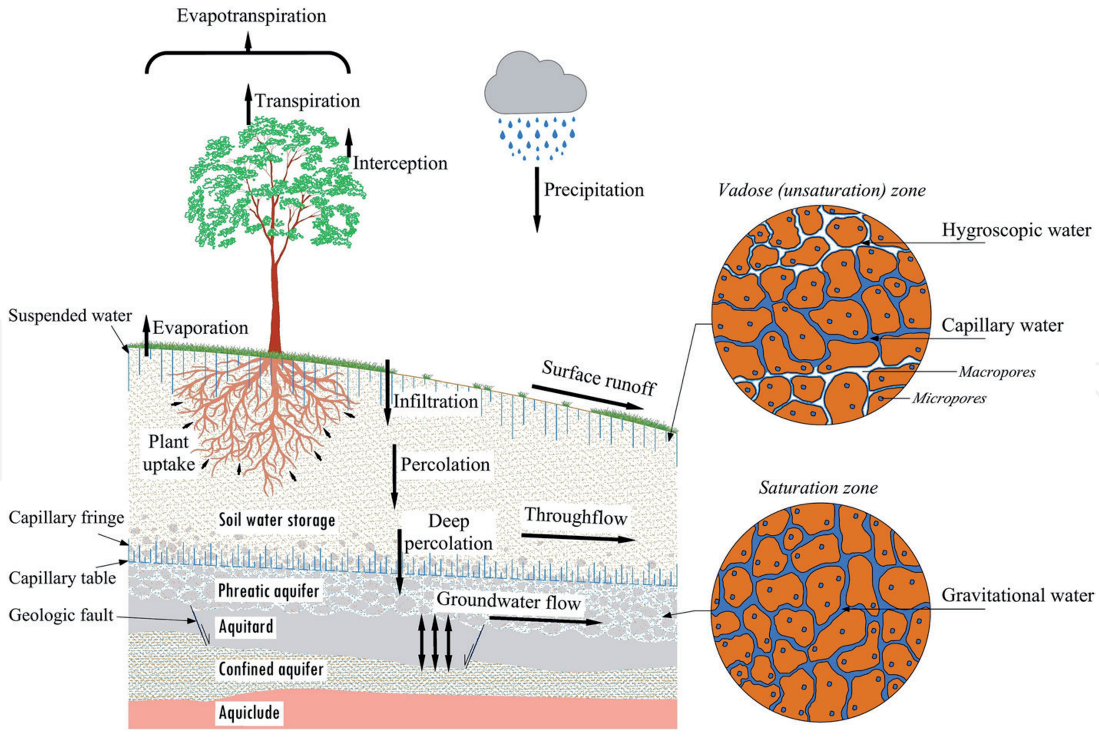

Figure 3.
The small water cycle in relation to geological subsoil: Communication of soil water and groundwater.

The subsurface water can be simply divided into soil water and groundwater. Although it is the same infiltrated surface water, these two divisions differ significantly from one another mainly in the ratio of forces acting on them. Soil water can be divided into three categories, namely adsorption, capillary and gravitational water.

The soil and rock environments can be classified into two zones in terms of saturation of the environment with water. The environment with the presence of air in pores may be termed the aerated unsaturated zone, where adsorption and pellicular water predominate, and gravitational water preponderates only for a limited period. On the contrary, the environment without the presence of air in pores (filled with water) is designated as a saturated aquiferous zone where gravitational water not bound by adsorption and capillary forces prevails. This water may be freely moving or maybe in the form of capillary water, filling small capillary pores.

The zone immediately adjacent to the aquiferous zone itself, that is, groundwater level, is the capillary fringe zone. Capillary water predominates in this zone. Adsorption water and, depending on the circumstances, gravitational water, may also be present. The capillary water completely fills capillary pores and is maintained by a capillary rise from the groundwater level in the zone. Capillary forces create a negative pore water pressure (under pressure). Thus, water cannot be collected from the environment and responds merely to groundwater level fluctuations. From hydrogeology and groundwater hydraulics, the capillary fringe zone can be included in the unsaturated (non-aquiferous) zone. Contrarily, in hydropedology, we work with the capillary fringe zone as with the saturated zone, which significantly affects the physico-chemical properties of the soil and is important in terms of the water supply of the soil environment in agriculture.

In terms of replenishing groundwater reserves by infiltration, gravitational water is the most significant. Gravitational water is used during infiltration, especially for the area of the rock environment above the groundwater level, that is the unsaturated environment. This includes the area between the groundwater level and the subsurface soil-water zone. The capillary fringe zone can also be ranked in this category.

The principle of water infiltration into the rock environment in the unsaturated zone can be expressed by gravitational and water potentials. In particular, infiltration depends on the characteristics of the particular soil or weathered particles (grain size, structure, organic matter content, geological activity, stratigraphy, etc.). Infiltration is determined experimentally for each specific soil type. For this purpose, moisture curves are used, which express the relationship between capillary pressure and moisture. The curves differ (hysteresis of the curves) when the soil is filled with water and when it dries.

Vertical flow of infiltrated water through the soil medium is such that during infiltration, pores in the upper soil layer become increasingly saturated with rainwater until saturation of the water-holding capacity is reached, whereupon the saturated zone shifts gravitationally deeper in the soil profile. This occurs because semi-capillary and non-capillary pores are systematically filled with water above the hydrolimit of the water-holding capacity and water moves with gravity in terms of saturated flow according to Darcy's law. As rainwater supply ends, due to termination of the particular rain event, saturation is reduced, and gravitational flow of water slows down and gradually begins to be controlled by the hydraulic conductivity of the particular type of the soil. Water dissipated in the environment and movement is practically stopped. If the rainwater supply is sufficient, infiltrated water may eventually reach the groundwater level, which is progressively raised. Due to gravitational drainage into the body of groundwater, the saturation of the soil environment gradually decreases, and the unsaturated zone is created again.

The process of infiltration through the soil environment substantially affects the quality of the infiltrated water, both positively, when it can significantly reduce pollution and thus protect groundwater against chemical or microbial contamination, but also negatively, in the case of contaminated soils (by means of anthropogenic activity, such as the. Enormous doses of industrial fertilizers applied to agricultural soils). Here, the contaminated infiltrated water can lead to the deterioration of the groundwater reservoir.

At present (i.e. in this current episode of anthropogenically driven climate change), it is of utmost importance to maintain the soil environment in as favorable as possible a condition in terms of enabling infiltration of rainwater into the soil environment or, more precisely, into the groundwater collector. The principal negative factors include soil compaction, the loss of soil structure and the reduction of organic matter content in the soil. These three factors significantly reduce the water-holding capacity of the soil, that is, the ability to retain and gradually release water, either in the form of evapotranspiration or infiltration into the groundwater reservoir. Vast impermeable anthropogenic surfaces (asphalt, concrete, roofs, etc.) also inflict a significant reduction in infiltration.

Nowadays, it is highly desirable to ensure infiltration of rainwater from these areas by appropriate technical and biotechnical measures, thus preventing their rapid surface or sub-surface run-off. Groundwater recharge in the Central European region historically took place in the colder half of the year, mainly from snowmelt. In this region this represented 3–4 months a year, when the zone between soil water and groundwater level was saturated and thus the regional groundwater reserves were continually replenished.

In the last 20 years, probably due to climate change, but also relevant alterations in landscape utilization, the saturation period of this zone has been significantly shortened and, consequently, there has been limited replenishment of groundwater supplies. A key role is played by noticeably lower snow reserves in the winter months, the overall temperature elevation during the year (i.e. increased evapotranspiration), and changes in rainfall distribution (accumulation of rainfall and decreased soil absorption capacity). Groundwater recharge is thus usually carried out during longer term, higher rainfall events. In the case of torrential rain, the surface zone is rapidly saturated and hence minimum infiltration, and erosive strong surface run-off occurs. Contrarily, during long-term moderate rain, the entire transitional zone gradually saturates to the groundwater level, and thus its reserves are replenished.

Groundwater reservoirs are also replenished at tectonic faults (fractures). The entire soil body need not be saturated within the process of infiltration, but gravitational water can flow because of fissure permeability, replenishing the groundwater reserves.

2.4 The soil-forest-water-civilization nexus

2.4.1 The elements of life

The soil-forest-water-civilization nexus has never been more important than at present. The Ancient Greeks recognized four basic elements of life: fire, water, air and soil. Yet throughout history, perturbation of the hydrosphere, atmosphere and geosphere has created huge issues for humanity and the rest of the Biosphere.

Trees are an essential component of most ecosystems on our planet, and the forests of the world play key roles in the hydrological cycle, nutrient cycles and the carbon cycle. Deforestation undermines ecosystem function upon which we rely for our very survival. Forests are major contributors to rainfall, with the Amazon rainforest producing some 70% of precipitation in the Rio de Plata river basin [72]. Forests also play a crucial role in temperature regulation, not only as repositories for carbon, but in terms of evapotranspiration and the production of microbial flora and biogenic volatile organic compounds which act as condensation nuclei for cloud formation and rain events. It is estimated that deforestation may account for as much as 18% of current global warming [73]. Forests purify surface and ground water [74]. Deforestation also reduces soil structure and organic carbon content, negatively impacting the water-holding capacity [75]. Environmental degradation leads to economic collapse and social instability [76]. Healthy forests and healthy soils are inextricably linked. Deforestation has three significant impacts: soil erosion, soil salinization and eutrophication.

2.4.2 Soil erosion

The incredible diversity of the biosphere in its many forms speaks to a complex foundation upon which such a magnificent edifice is built. Yet terrestrial ecosystems are almost entirely dependent upon a thin, living skin, stretching across some fifty million square kilometers, but with a mean depth of only 15 cm: the soil. Most plants need soil, and plants form the basis of most terrestrial food chains. Yet in the last 150 years, we have lost 50% of the planet's topsoil through soil erosion. Lester W. Brown, the President of the Earth Policy Institute, has written that civilization can survive the loss of its oil reserves, but it cannot survive the loss of its soil reserves [77].

Soil erosion is not a new problem. Plato bemoaned the fact that the soil of Greece was, by his own time, eroding, observing that 'what now remains compared with what then existed is like the skeleton of a sick man, all the fat and soft earth having wasted away, and only the bare framework of the land being left' (in Glacken [78]). Around 60 BC, Lucretius, the philosopher and poet, recognized the seriousness of soil exhaustion in Italy. He thought that the Earth itself was dying [79]. A comprehensive review of the historical significance of soil erosion and the contribution of deforestation to this can be found in Dotterweich [80].

Accelerated erosion has been occurring in Britain since the first clearances of primeval forest 5000–6000 years ago [81]. While early human agriculturalists used hand-held tools, maintaining a rough surface, allowing infiltration, later iron tools smoothed the surface, leading to run-off and erosion. By medieval times, many European villages had been abandoned as a result of soil erosion, elevating food prices due to crop failure and leading to social instability [82]. Today, 751 million ha of the planet's soil has been severely eroded [83]. Overgrazing by livestock and intensive agricultural practice has led to huge swathes of erosion. But deforestation has been one of the most significant contributors to the erosion crisis facing the planet. One and a half million square kilometers of dense tree cover were lost between 2000 and 2012 [84].

Shallow tree roots bind soil aggregates, increasing soil cohesion, while protecting against surface wash erosion. Deeper roots anchor the regolith to the bedrock, preventing landslides, debris flows and mudflows. Trees also reduce the load from lower soil moisture through evapotranspiration [85].

Soil production takes many years, and today losses far exceed formation. In China, the soil is being lost 54 times faster than it is being formed, leading to huge economic and social insecurity. In the case of China, soil loss accounts for the loss of 42 billion dollars per year, impacting 170 million people [86].

It is thought that the Babylonian and Sumerian kingdoms collapsed due to soil erosion, blocking irrigation systems [87]. Once the soil is gone, the risk of flooding after heavy rain increases dramatically. The trees form a crucial link in the hydrological cycle, shifting water from the soil back to the atmosphere.

Wind erosion is an equally serious threat to humanity. The Dust Bowl in the USA stands as a striking example, where a 10-year collapse in agriculture was due to soil erosion driven by agricultural mismanagement in the 1930s. On Black Sunday, 14 April 1935, the sunlight was blocked out by the dust, when three million tonnes of topsoil from the Midwest was blown into the atmosphere. The Dust Bowl forced around two and a half million people to flee from their mid-west farms and head to California.

2.4.3 Eutrophication

Soil erosion contributes to another major threat to our planet, eutrophication. Eutrophication is caused by nutrients being washed into the hydrosphere from the soil. Soil itself is a nutrient bomb, and so erosion delivers huge amounts of nutrients into streams, rivers, lakes and the oceans, leading to hypoxia, cyanobacterial blooms, toxic red tides and fish death. In Europe, Asia and North America, 50% of freshwater bodies are now eutrophic, while dead zones are a regular occurrence in the oceans, devastating fish populations. In the US alone, eutrophication costs around 2 billion dollars each year [88].

2.4.4 Soil salinization

Deforestation also leads to soil salinization. Currently, 25% of the world's cropland is affected, while in Africa, this figure is 50% [89]. By 2050 it is estimated that some 50% of cropland will have productivity halved due to build-up of salt in the surface soil [90]. Nagendran [91] observes that salinization is the most striking effect of agriculture in all parts of the world. Soil salinization is very difficult to reverse.

Salinization is a particular threat to Australian agriculture, given that most of the country is desert. In the Murray Darling Basin, 63% of the forested area has been converted to cropland in the last 200 years [92]. This has led to increased downward water fluxes below the root zone by one to two orders of magnitude [93] because the trees are no longer performing their role as water shifters from soil to atmosphere. This has resulted in a rapid rise in the groundwater table at a rate of~1 m year^{-1}, leading to the salinization of some 5.7 million ha of farmland, devastating harvests [94].

Similar large-scale salinization events have been recorded in California, north-west India and much further back in time, in Ancient Mesopotamia [95–97].

2.4.5 The biotic pump

Finally, deforestation leads to huge changes in the rainfall distribution patterns on our planet. The biotic pump theory [98] proposes that evapotranspiration creates lower pressure above forest canopies, drawing in moist air from the oceans, and supplying precipitation far inland. The reduction in evapotranspiration as a result of deforestation leads to an increase in the height of the convective boundary layer because of the stronger sensible heat flux over pastures. This is less conducive to rainfall formation. Deforestation is thought to have contributed 60% to the drought conditions that led to the collapse of the Mayan empire [99].

Much like climate destabilization, the biotic pump acts across national boundaries, requiring international collaboration. If inland nations carry out significant deforestation, the impacts are not only felt within that nation, in terms disruption to the local hydrological cycle, exacerbating flood risks, landslides, soil erosion and water purity, but also in nations that lie between the oceans and the deforested region, as the pressure gradient is no longer as strong, reducing the strength of the pump.

Critics of the biotic pump theory have argued that air movements as a result of condensation are multi-directional, representing an isotropic (uniform in all directions) process and this means that there will not be any uni-directional, net flow from ocean to continental landscapes [100]. In this orthodox approach, mass air movements alone drive the hydrological cycle across latitudinal cells set up by temperature gradients due to the uneven heating from the sun as a result of the axial tilt and curvature of the Earth.

However, it has been demonstrated experimentally that condensation can trigger anisotropic, uni-directional flow, supporting the biological pump theory [101, 102]. Sheil [103] points out that disruption of the biological pump through deforestation can lead to dramatic, non-linear transitions in local climate, from wet to dry regimes. Interestingly, reforestation can lead to a similarly dramatic transition in the opposite direction, from a dry to a wet local climate regime [103]. However, there is no guarantee that reforestation will return the region to an identical ecological state as that prior to deforestation, as species may have suffered extinction, and recolonization routes may no longer exist.

2.4.6 Regime shifts

Of greater concern yet is the fact that such widescale changes resulting from deforestation and the destabilization of the soil-water relationship may lead to regime shifts. Lees et al. [104] define regime changes as abrupt changes on several trophic levels, leading to rapid ecosystem reconfiguration between alternative states. Both structures and processes are transformed and such changes, in turn, result in significant alterations in ecosystem services [105, 106]. Complex non-linear systems, such as ecosystems, become vulnerable to phase shifts, where relatively small changes in an already stressed system can result in the irreversible collapse of the system, switching, for example, from a wet forested state to a dry savanna, and creating an alternative equilibrium, with devastating consequences [107–109]. Such shifts are more likely to occur as anthropogenic perturbation increases [110].

Of additional concern is the reality that ecosystems are interconnected to other ecosystems, to such an extent that a regime change in one part of the biosphere can catalyze changes in other ecosystems. One example relates to regime changes in the Arctic, wherein sea-ice changes lead to reorganization of tropical convection that in turn triggers an anticyclonic response over the North Pacific, resulting in significant drying over California [111], potentially leading to regime change. Ecosystems are sub-systems, not isolated systems. Thus, changes run throughout the biosphere, impacting on all levels of organization, in non-linear ways. We would expect this in any self-organizing system, where feedback dictates context and change. One such conduit is the soundscape, wherein ecological simplification can lead to radical transitions at the ecosystem level facilitated by the absence of audible cues [112]. Another feedback conduit is the hydrological cycle, and forests play a central role here. Interfering with water relations can have huge impacts on regime stability and the spread of regime shifts across the biosphere [113].

3. Conclusion

Forest soil water balance plays an essential, central role in ecosystem functionality. The modification of water balance within forests can enhance self-regulation of all ecosystems in a landscape, but intensive, anthropogenic landscape transformation can negatively impact it. Human activities, such as deforestation, have had damaging impacts on evaporation, precipitation and run-off. The protection of forest water balance has been highlighted as a priority through coordinated research based on analysis of soil properties and ecosystem function restoration. Underpinning any hope of achieving this lies the urgency of attaining a sustainable relationship between human needs and natural resources.

Thus, we see that forests are essential components in both the hydrological cycle and in soil functionality, while also playing a crucial role in the carbon cycle. Forests, much like soil and water, are currently under-appreciated by the human race, yet our futures rely on their restoration and respect. Kravčík [114] have called for a new paradigm in order to rescue humanity from a crisis beyond our imagining: regime shifts and the functional collapse of the terrestrial and aquatic ecosystems. Such a paradigm no longer views water as an isolated entity, a fixed renewable resource and having little to do with the suite of environmental crises facing us, along with the coming economic and societal collapse undoubtedly awaiting us on our current trajectory. Instead, they call for a prioritization of the restoration of the water balance at all levels, but particularly at the level of the small water cycle. Intrinsic to this is healthy soils and healthy forests. The soil-forest-water-civilization nexus must urgently be understood as a synergy, connected and united within the Earth system if we are to find a constructive way ahead and a place for our own sub-species within the biosphere.

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