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Changes of Water Budget during Ecosystem Development in Post-Mining Sites at Various Spatiotemporal Scales: The Need for Controlled Systems

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Abstract

This chapter describes the development of the soil-water budget at various spatiotemporal scales, including an example of post-mining sites. This includes the formation of soil aggregates and porosity, the development of water retention in the soil profile, and water losses by runoff and evapotranspiration. It is emphasized that the development of soil-water retention is closely linked to carbon storage in post-mining soils, which is strongly affected by litter quality. Plants with a high C:N ratio of litter feature most of the organic matter in Oe and litter layers, which results in a lower soil-water storage, whereas soil covered by vegetation with low litter C:N ratios produces organo-mineral aggregates and deeper A horizons that promote water storage. Moreover, the need for controlled catchment conditions to get a better understanding of how these processes on various spatiotemporal scales interact is emphasized.

Keywords: soil aggregates, soil profile, catchment, water retention, runoff, evapotranspiration

1. Introduction

Water movement in the landscape is a complex process, consisting of many connected and interacting processes at various spatiotemporal scales. These include processes on the level of soil aggregates, which affect infiltration and the ability of soil to hold water. Formation of macropore connectivity and surface channels, which affect surface and subsurface runoff.

Bedrock weathering and transportation processes affect redistribution of clay and nutrients. Organic matter in the soil profile and in the landscape feeds back to water movement and storage in the ecosystem. Many of these processes are affected by plants and soil biota, such as aggregate formation, creation of a porosity network, water intake by plants, or interception of rain by vegetation. Water enters the ecosystem by rainfall and leaves it by runoff and evapotranspiration. In the ecosystem, water can be stored in vegetation and in soil. The previous research shows that the ability of soil to store water is closely related to storage of soil organic matter (SOM) [1]. During ecosystem development, a vegetation cover develops, which reduces water input to the soil by interception and increases water loss by transpiration, but reduces evaporation from open soil surfaces. Vegetation also produces litter and root exudates, which are important for the activity of soil biota. Soil biota, which mostly directly or indirectly feeds on plant products, affects aggregate formation, storage of SOM, and distribution of SOM in the soil profile. Certain types of plants promote the activity of specific assemblies of soil biota, which affect certain patterns of SOM storage and distribution in soil. Plants with a conservative growing strategy promote a soil community that causes no or little bioturbation, which results in a thick litter and Oe layer on the soil surface. On the contrary, fast-growing plants promote intensive bioturbation by soil fauna and the formation of a deep A organo-mineral soil horizon [2–5]. This affects overall SOM storage [6, 2], which very likely affects water storage in soil as well [1]. Plants affect water movement in the system also by other means, such as by a different degree of interception and fate of water trapped by interception or different water consumptions and transpiration rates. Although all of these parameters have been intensively studied, we have only little information about how individual plant traits that affect SOM behavior in the soil relate to various parameters determining water storage and movement in the ecosystem. These interactions have been intensively studied in terms of the relationship between soil development and SOM storage, and although there is a general understanding that SOM may be closely related to soil-water, much less is known about factors and mechanisms affecting the water regime development during ecosystem development.

Mining and open-cast mining cause large disturbances to ecosystems. Most of the affected ecosystems are completely erased, either excavated or buried under overburden, which usually substantially differs from well-developed soils. In addition to texture, the hydrophobicity of the substrate [7], lack of macropores, soil compaction, and sometimes salinity are factors that can affect soil conditions, particularly the soil-water regime [8, 9]. The study of ecosystem development at these sites has a large practical impact. Post-mining sites also represent locations that have a great potential to study these processes. One of the reasons that make these sites suitable for the study of ecosystem development is the presence of sites of various ages, so-called chronosequences, where ecosystem development can be studied by comparing individual parameters or processes on sites of different ages. This approach, called also space-for-time substitution, allows the study of long-term processes in a very short time. Despite its clear advantages, this type of investigation has also its limitations, as each site develops in a specific trajectory, which may differ from the general chronosequence pattern. Another reason why post-mining sites are good systems to study successional processes is that these sites offer a combination of parameters that may not occur elsewhere and are suitable for large-scale landscape manipulations, which would be technically hardly possible or ethically questionable elsewhere.

The aim of this contribution is to describe processes that affect the development of the water regime at post-mining sites after open-cast coal mining near Sokolov based on the extensive study of chronosequences at these sites. In addition, the idea of constructing isolated, controlled micro-catchments that would allow the investigation of these processes on various levels, from soil aggregates to the landscape scale, is presented.

2. Water regime development in chronosequence studies across various spatiotemporal scales

As already explained, the development of a water regime can be divided into two parts: the development of soil, which stores water in the ecosystem, and the development of vegetation, which is an important consumer of water. However, vegetation also determines many transportation processes, which affect movement of soil between ecosystem compartments and surroundings, and directly or indirectly determines soil-forming processes. In this chapter, we will follow the formation of soil aggregates and their role in water retention, followed by the development of the whole soil profile and, finally, the development of vegetation and its role in soil profile development.

2.1. Microscale processes of aggregate formation and porosity

Soil aggregates are secondary particles formed through the rearrangement and cementation of primary mineral particles with SOM [10]. They are often grouped by size into macroaggregates (250–2000 μm) and microaggregates (53–250 μm) [11–13]. A highly influential model on the formation of aggregates was published by Tisdall and Oades [14] that was later modified by Oades [15]. Based on these models, it is now commonly accepted that macroaggregates form first, mainly by the entanglement of particles by fungal hyphae and roots (temporary binding agents) and around fresh particulate organic matter (POM) inputs. When these temporary binding agents and the POM in macroaggregates decompose into fragments, coated with mucilage produced during decomposition, they become encrusted with clay particles and thus form the nucleus for microaggregates within macroaggregates [11]. As a consequence of this “aggregate hierarchy,” macroaggregates contain more C and higher amounts of labile C as compared to microaggregates, where SOM is more processed and regarded as relatively stable over longer periods of time. However, because of the higher lability of macroaggregates, the stability of microaggregates (contained within macroaggregates) depends to some extent on the turnover of macroaggregates. Apart from the earlier mentioned roots and fungal hyphae, factors generally positively influencing the formation and stability of aggregates are soil bacteria, producing extracellular polymeric substances, thereby cementing soil particles predominantly in microaggregates [14, 15], and the soil fauna, especially earthworms, forming stable casts and exerting pressure on the walls of their burrows, thereby compacting the soil [13, 16]. At initial post-mining sites, the clay content is another crucial factor as it forms the backbone of stable microaggregates [16]. At post-mining sites, overburden can be formed by clastic material, such as sand or gravel, but often it is deposited in the form of less consolidated material, such as shales, madstones, or stones [17, 18]. Weathering of this material and a gradual increase of the clay content is an important step in soil aggregate

formation [19]. At many post-mining sites, aggregates are formed from clay or organic matter that serve as cementing material and fine pieces of weathered consolidated material [20].

Soil fauna can also promote aggregate formation and enhance water-holding capacity by transformation of organic matter. Analyzing soil cores filled with leaf litter and bionid fly larvae revealed that even litter-feeding fauna can increase the ability of soil to hold water just by turning litter into fecal pellets, which increase water field capacity manifold. Litter transformation into fecal pellets causes fragmentation of the leaf, breaking the cell walls, and opens these capillary surfaces to be accessible to soil-water. Moreover, compaction of material inside the fecal pellet creates additional capillary pores by compacting consumed litter. These holo-organic aggregates can, in some soils, form layers (Oe layer) in several centimeters thick [1, 21–23]. Even more important is the formation of soil aggregates by earthworms [24–27], which can also contribute significantly to the greater ability of soil to hold water [22, 28]. Increased water-holding capacity is, however, in both cases mentioned above accompanied by an increase in wilting point. Nevertheless, in both cases we can conclude that the soil fauna enhanced the ability of soil to hold water, which was then potentially available for plants as increase in water field capacity was in both cases higher than the increase in wilting point (**Figure 1**). Earthworm-created aggregates may also promote formation of larger soil pores between aggregates, which can enhance infiltration and decrease runoff and erosion. However, some other soil biota, namely, ants, might accumulate unconsolidated soil at the surface, which can be easily removed by erosion and in fact increase erosion loss of soil from the plot [29].

Besides aggregate formation, soil macropore development is important in post-mining soils. Several studies indicate a gradual increase of porosity in aging post-mining soils [19, 30]. Besides physical processes and roots, earthworms, ants, and also termites in tropical and subtropical parts of the world are most commonly mentioned in this context [31–35]; however, a much larger diversity of soil invertebrates, such as solitary bees or wasps, spiders [36], coleoptera [37], orthoptera, and even crayfish [38], significantly contribute to biopore formation. These macropores can differ substantially in size and shape and in how they

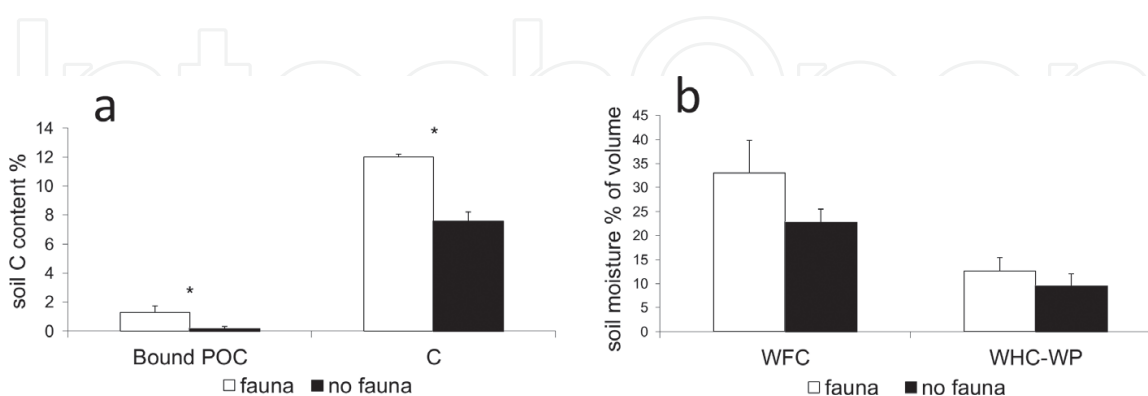


Figure 1. Carbon content in bulk soil C and in proportion of C bound in aggregates from total soil mass (POC bound) in soil aggregates created by soil fauna (specifically by earthworms) and other aggregates (based on data from [20]) (a), water field capacity (WFC), and difference between WFC and wilting point (WFC-WP) (b), for clay post-mining substrate closed in a macrocosm with and without access of soil fauna for 3 years based on data from [22]. *significant difference between fauna-accessible and fauna-non-accessible treatments (t-test, $p < 0.05$).

are formed. Roots basically push themselves in the soil with the help of lubrication effect of root exudates. Similarly, earthworms burrow themselves into the soil by pushing soil to the side, forming a layer of more compacted soil along the burrow wall, which is covered by earthworm mucus. The area in which earthworms actively burrow is called the drilosphere. Ants and most other arthropods commonly dig into the soil, and excavated soil can be transported out from the hole, used to fill unused cavities, or partly spread on the walls to form a ceiling; various other ceilings such as spider net can be used in biopores [33, 36]. Despite the fact that this large variability in biopore construction is well known, a deeper understanding of how individual “construction patterns” affect the function of biopores in soil is still lacking.

2.2. Upscaling small-scale processes to whole soil profile development

Here, we now explore how the small-scale processes described above transfer to the development of the whole soil profile. We use an example of two 20-year-old soils developing de novo at two adjacent locations. The first site is reclaimed leveled and planted with alder (*Alnus glutinosa*) seedlings. Alder is a nitrogen-fixing tree which provides litter with low C:N ratio. Consequently, there were abundant macrofauna community with a high density of earthworms, *Lumbricus rubellus* and *Aporrectodea caliginosa*, in alder site. In contrast, the second site is unreclaimed and keeps its wavelike character created by heaping; it is vegetated by a spontaneous regrowth dominated by willow, birch, and aspen (*Salix caprea*, *Betula pendula*, and *Populus tremula*) and had a less abundant macrofauna, and earthworm species that mix litter with soil are missing. The consequence of this absence of mixing earthworms on spontaneous regrowth was a thick fermentation layer on the soil surface. In the contrary, in the alder plantation, a litter has been immediately fragmented and mixed into the soil, forming an organo-mineral layer [23]. Previous micromorphological observations showed that worm casts can contribute about half of the solid fraction of soil [23]. Intensive mixing of litter into mineral soil can be, under suitable conditions (under trees producing easily available litter such as alder or lime), a reason for fast formation of organo-mineral A layer which can up to 15 cm thick after 40 years of development in some soils. Looking at various soils developing on the same post-mining heap, we can see that the ability to hold water closely connected with organic matter accumulation in these soils (**Figure 2**). As has been shown previously, accumulation of organic matter in mineral soil closely corresponds with bioturbation caused by soil fauna, primarily earthworms [6]. The highest water field capacity was observed at alder stands, which produces easily decomposable litter and is subject to intensive bioturbation by earthworms. In contrast, a lower water field capacity was found in coniferous species with very limited soil faunal activity (**Figure 2**). However, as already mentioned, at the level of individual soil aggregates and also in the level of bulk soil, the wilting point correlates with water field capacity. This means that alder sites have higher water field capacity but also higher wilting point as compared to regrowth sites (**Figure 2**). The water regime at both sites after 30 years of development was basically similar, but higher moisture and consequently higher soil-water storage were found at the alder plantation (**Figure 3**), which is consistent with the already reported high water field capacity at these sites [12, 30, 39].

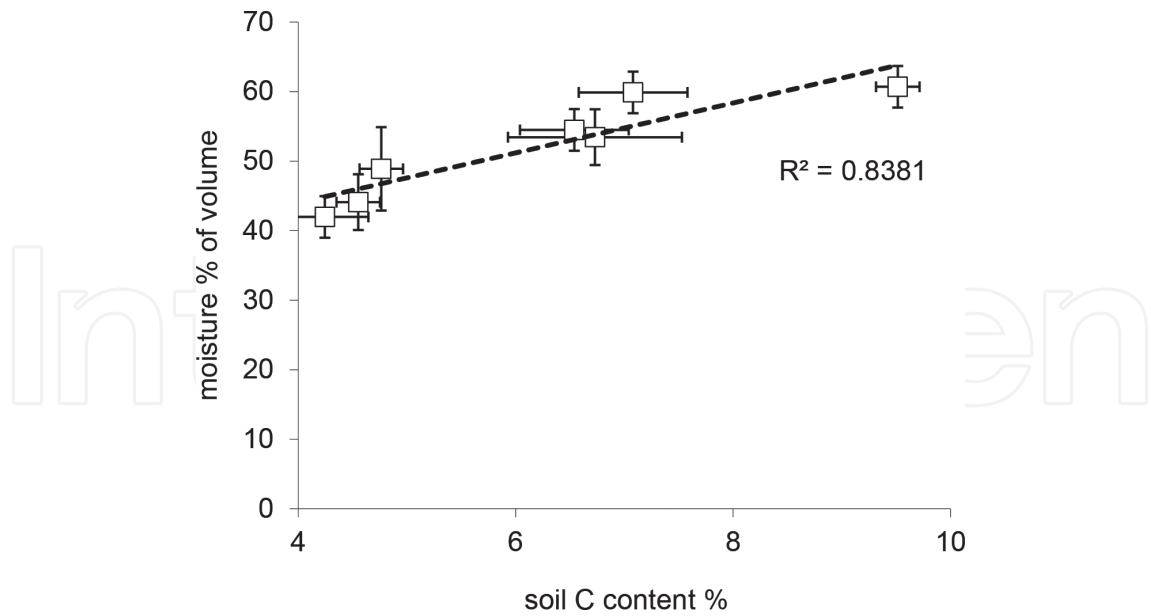


Figure 2. Water field capacity (WFC) of 30-year-old post-mining soils developing on the same clay soils under various tree species in relation to soil carbon content in particular sites based on data from [3].

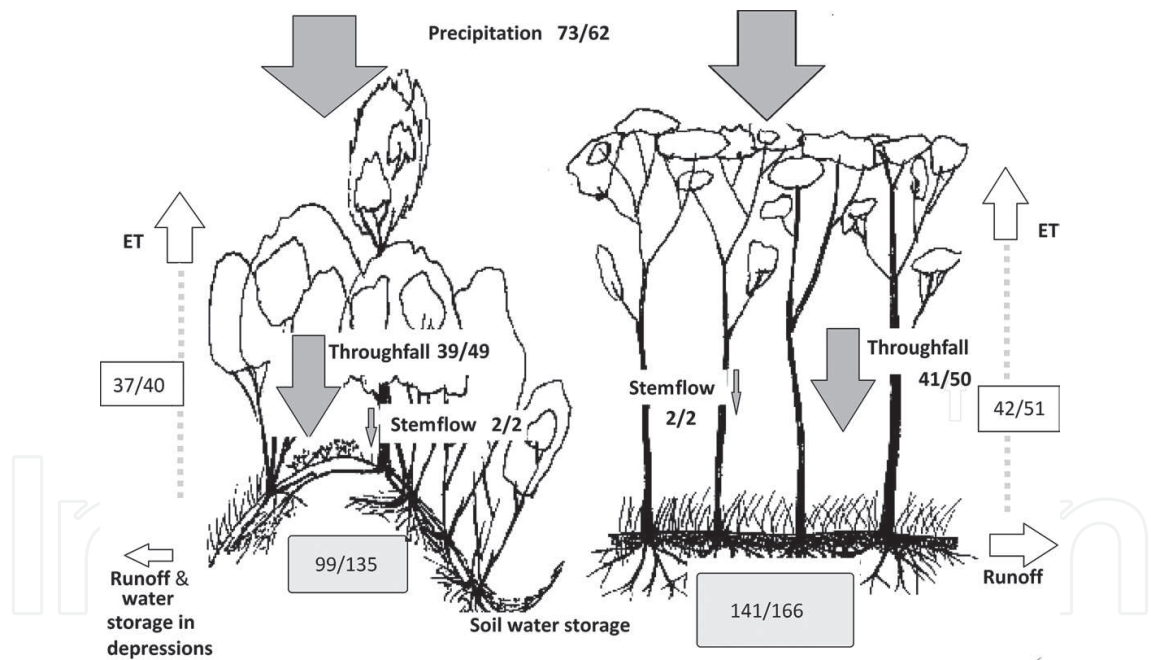


Figure 3. Monthly water budget of unreclaimed mean sites without any technical reclamation spontaneously covered by natural regrowth dominated by *Salix caprea* and *Betula pendula* (left) and reclaimed sites planted by alder (right) both sites about 30 years old, based on data from [39]. Data are monthly mean flows during vegetation season/outside vegetation season in mm or average stock in vegetation season/outside vegetation season.

2.3. Vegetation development and its role in the water regime

With increasing succession age, plant cover increases. Dynamics of this increase may certainly vary between various types of vegetation. For example, Frouz et al. [40] investigating reclaimed alder plantations and unreclaimed post-mining sites, found that biomass of reclaimed sites

increased faster early after reclamation, but later on, differences between reclaimed and unreclaimed sites decrease, and older unreclaimed sites show even higher biomass than reclaimed ones. With increasing vegetation cover, water consumption by transpiration also increased [30, 39]. This can be ascribed to an increased temperature buffering. In a study [41] the difference between morning and afternoon temperatures was assumed as a measure of the temperature buffering ability of the ecosystem, which is proportional to the amount of water transpired by evapotranspiration. Buffering increased with increasing plant cover measured as NDVI but also depended on the type of vegetation; reclaimed sites had significantly higher buffering than unreclaimed sites. This indicates a higher water transpiration at reclaimed alder plantations than at unreclaimed woody regrowth sites [41]. A slightly higher water consumption at reclaimed alder plantations compared to unreclaimed plots has been indicated also by a complete water budget on these plots [39].

3. Potential of using controlled catchments in the study of water regime development at post-mining sites

What has been mentioned above opens many potential hypotheses about the development of the water regime in post-mining soils. It seems that soil-water storage is closely linked with SOM storage. Similarly, as proposed by Cejpek et al. [39], plants with a fast-growing strategy, which tend to store more SOM in mineral soil [3, 6], also tend to produce soil aggregates with more bound OM [20] and, consequently, soils store more water [19, 22, 30, 39]. This concept opens many other questions, such as how these parameters relate to the water balance (e.g., to runoff and evapotranspiration), how historical changes in soil carbon storage and water retention affect subsequent ecosystem development, and many others. Answering these questions may be interesting not only for a better understanding of ecosystem development at post-mining sites but also may have more general implication. However, answering these questions faces also many methodical challenges. With common instrumentation we are not able to follow that part of the landscape with woody vegetation that would realistically allow the measurement of all the water movement, including surface and subsurface runoff. In order to answer these and other questions, we plan to build small hydrologically isolated micro-catchments on a heap (similar to rainy hill of Chicken creek catchments [42]) in a way that the installed devices allow comprehensive monitoring of the flow of water and nutrients through the ecosystem as well as the exchange of gases between the ecosystem and the surrounding atmosphere. In particular, we will measure the rain water input, including dry and wet deposition, surface and subsurface runoff, the content of key elements of the discharge, water movement in the soil profile, total radiation, carbon exchange (CO_2) between the atmosphere and the whole ecosystem, and also between soil and atmosphere. The area itself will be divided into four micro-catchments with an area of about 0.25 ha each, two of which will be planted with alder and the other two will be left uncultivated. For each pair of areas (reclaimed and uncultivated), one eddy covariance tower will be located in the direction of the predominant winds. The area will then be equipped with container lysimeters and access shafts allowing for the easy implementation of additional ad hoc experiments.

The main component of the entire experimental catchments will be the monitoring of the water flow. For separation of surface and subsurface runoff, the underground clay layers will be compacted at a depth of 2 m to create an impermeable layer. This impervious layer will lead into a collecting channel fitted with a specific overflow and a subsurface drainage monitoring device. Another specific collecting trough fitted with a further measuring overflow and measuring equipment will then be placed on the surface of the terrain. This will allow a separate observation of surface and subsurface runoff. The flow monitoring devices will also take samples of water to measure flows, which will then allow the calculation of the balance of substances moving with the water.

The water input into the catchment area will be monitored by a set of rain gauges that will both monitor rainfall dynamics and capture rainwater for subsequent chemical analysis.

In addition to the water flow and gas exchange facilities, access shafts will be located in the catchment area. These are plastic shafts equipped with observation windows and preset points where additional accessories can be installed. This will allow the installation of any instrument to monitor the development of soil and nutrient flow during the operation of the experimental basin without the need for further disturbance, which is key to the function of the river basin. The area will also include container lysimeters to monitor soil development and to perform manipulation experiments. Those will be particularly valuable in an experiment aiming at upscaling processes from the soil aggregate level to the whole soil profile.

4. Conclusions

Large-scale hydrological parameters that determine water movement in the landscape level can be tracked in small-scale processes on the level of individual aggregates or soil pores. This tracking indicates that both of these processes can be driven by growth strategy of plants. Experiments in controlled conditions where both macro- and microscopic processes can be studied in more details are needed for better understanding of these interactions.

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