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The effect of the bulk density and the decomposition index of organic matter on the water storage capacity of the surface layers of forest soils

Anna Ilek [a,*], Jarosław Kucza [a], Małgorzata Szostek [b]

[a] Department of Forest Engineering, Institute of Forest Ecosystem Protection, Faculty of Forestry, University of Agriculture in Krakow, Al. 29 Listopada 46, 31-425 Krakow, Poland
[b] Department of Soil Science, Environment Chemistry and Hydrology, University of Rzeszow, ul. Ćwiklińskiej 2/D3, 35-601 Rzeszow, Poland

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ABSTRACT

Forests play an extremely important role in the formation of water circulation in a catchment. Despite numerous studies concerning the relations between forest and water, many problems still remain unexplained. Among them is the influence of the species composition in a stand on the water storage capacity of forest soils, especially of their surface horizons, whose physico-chemical properties are directly affected by the stand. The knowledge of those interactions is significant not only in the aspect of modelling of hydrological phenomena occurring in forest ecosystems but may also be helpful in indicating the directions of stand rebuilding aimed at extending the water-protective functions of forest.

The aim of the present research is to analyse the influence of the bulk density and the index of decomposition of organic matter on the water storage capacity of the surface layers of forest soils formed under beech (*Fagus sylvatica* L.) and fir (*Abies alba* Mill.) stands in southern Poland. The water storage capacity of individual forest soil horizons shows a distinct relationship with their bulk density. In beech and fir stands there is a critical value of bulk density, amounting to 0.48 and 0.51 $g \cdot cm^{-3}$, which corresponds to culmination of the water storage capacity. A strong correlation has been shown between water storage capacity and the index of decomposition of beech and fir organic matter. It has also been found that the index of decomposition of organic matter and the degree of saturation, an indicator of water-filled voids in the soil, can constitute useful measures for describing and comparing the water storage capacity of the surface layers of forest soils formed under stands with a different species composition.

1. Introduction

From the point of view of forest hydrology, water dynamics in the soil is one of the most important elements of the water balance of forest communities (Kucza, 2007). It is a reflection of the current demand of a stand for water used both for transpiration and for evaporation from the soil surface. A special role in shaping the water storage capacity of forest soils is played by organic and humus horizons, containing significant amounts of organic matter. These horizons are often disregarded when calculating the water balance of forest ecosystems (Greiffenhagen et al., 2006).

The water storage capacity of the organic horizons is very important hydrologically and environmentally. For example, Leuschner (1998) reported that the organic horizons can retain from 2 to 4 times more water than the mineral soil. According to Tsiko et al. (2012) interception of water on the surface of plants and litter can constitute a total of 37 to 50% of all rainfall. Water stored in organic soil horizons is an important source of water for plants (Sharratt, 1997). By protecting the mineral soil from the direct impact of raindrops, the organic horizons prevent erosion, maintain the soil infiltration capability and also prevent evaporation from the underlying mineral soil (Onda and Yukawa, 1994; Tamai et al., 1998; Sharafatmandrad et al., 2010). Water retained in the organic horizons is of large significance for the water balance of the soil profile and the entire forest ecosystem (Laurén and Heiskanen, 1997).

The pore structure of the soil and its hydrological properties are influenced by many factors, including the mineral composition of the soil, the presence of rock fragments in the soil, the quantity and the degree of decomposition of organic matter, the presence of plant roots, the activity of soil organisms and land use (Zawadzki, 1970; Celik, 2005; Kodešová et al., 2006; Bormann and Klaassen, 2008; Ruiz Sinoga and Martinez Murillo, 2009). In light of individual studies it can be concluded that the hydrological properties of organic soil horizons are influenced by the type of vegetation and the species composition of the stand. For example, Tsiko et al. (2012) showed that the water storage capacity of the litter horizon in the *Brachystegia spiciformis* Benth. stand and in the litter formed under herbaceous vegetation amounts to 1.8 and 1.5 mm respectively. According to Gerrits (2010), cedar litter has only about one-half of the water storage capacity (1.0 mm) of beech litter (1.8 mm). For pine litter (*Pinus radiata* D. Don) and eucalyptus

* Corresponding author.
E-mail address: a.ilek@wp.pl (A. Ilek).

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litter (*Eucalyptus* spp.) Putuhena and Cordery (1996) obtained the water storage capacity of, respectively, 2.3 and 1.4 mm. According to Ilek et al. (2015) spruce litter (*Picea abies* (L.) H. Karst) retains nearly three times more water than beech litter (*Fagus sylvatica* L.) and almost twice as much as fir litter (*Abies alba* Mill.).

Particular sublevels of the ectohumus of forest soils often have different water storage capacity due to differences in the physical properties of those horizons, such as density and porosity as well as the advancement of organic matter decomposition processes (Sato et al., 2004; Zhang et al., 2006; Kucza, 2007; Ilek, 2014; Ilek et al., 2015). The water storage capacity of forest soils is affected by many factors, which include: the mass of the litter, its structure, the percentage of its individual components, wettability of the soil material, the degree of organic matter humification, the water content in different horizons immediately before the onset of precipitation, characteristics of rainfall and the ability of organic matter to shrink and swell under the influence of drying or wetting (Walsh and Voigt, 1977; Grelewicz and Plichta, 1983, 1985; Prusinkiewicz and Kosakowski, 1986; Suliński, 1993; Leuschner, 1998; Kucza and Suliński, 2000; Sato et al., 2004; Kucza, 2007; Homa and Osuch, 2009; Zhang et al., 2009; Li et al., 2013).

Hydrological importance of organic matter is the subject of research conducted both in field conditions and in the laboratory (Bernard, 1963; Golding and Stanton, 1972; Kosturkiewicz, 1977; Prusinkiewicz and Kosakowski, 1986; Naeth et al., 1991; Suliński, 1993; Schaap et al., 1997; Homa, 1998; Leuschner, 1998; Kucza and Suliński, 2000; Kucza, 2003a, 2003b, 2003c; Kiss et al., 2005; Kucza, 2007; Homa and Osuch, 2009; Park et al., 2010). The existing state of knowledge about the water storage capacity of the surface layers of forest soils still does not allow for modelling the dynamics of their ability to retain rainwater and of its infiltration into the soil profile. The difficulty in comparing the results of these studies, often conducted under different climatic conditions, is due to non-uniform application of research methodology, resulting from different research assumptions and from conducting research on a variety of habitats, often in stands which are mixed and thus differ in the susceptibility of organic matter to decomposition.

The present study focusses on the surface layers of mountain forest soils formed under beech (*Fagus sylvatica* L.) and fir (*Abies alba* Mill.) stands. The aim of the present research is to analyse the influence of the bulk density and the index of decomposition of organic matter on the water storage capacity of the surface layers of forest soils formed under stands which differ in their species composition.

In this study, the surface layers of soil are defined as the top soil layer (with the thickness of up to 12 cm) consisting of: 1) the organic horizon (ectohumus), which contains the litter horizon Ol and the detritus horizon Ofh, 2) the humus horizon A (endohumus) and 3) the mineral horizon, 3–4 cm thick, lying directly below the humus horizon.

2. Materials and methods

2.1. The study area

The study was conducted in Tokarnia Forest Sub-District, located in the area of Myślenice Forest District (Regional Directorate of the State Forests in Krakow) in the Beskid Makowski Mts (southern Poland). In order to obtain diversity of physical properties of the surface layers of forest soils, there were selected 10 plots located in fir stands (*Abies alba* Mill.) and 10 plots located in beech stands (*Fagus sylvatica* L.), varying in terms of age. The soils of all studied stands were formed out of weathered Magura sandstone and classified as acid brown soil (Forest Management Plan, 2008). The characteristics of each research plot relating to age, the average diameter at breast height and height of the stand, as well as the altitude, aspect and inclination are shown in the study by Ilek et al. (2015).

2.2. Research material sampling

Field work was conducted from September to November 2013. Research material in the form of soil monoliths and samples was collected at the distance ranging from 1.0 to 1.5 m from tree stems, within the range of tree crowns. From each research area 1 soil monolith and 2–3 soil samples were collected. The study involved a total of 20 monoliths (10 fir and 10 beech ones) and 46 soil samples, of which 20 came from fir stands and 26 from beech stands. The soil monoliths comprised the surface layer of forest soils and contained the horizons: litter Ol, detritus Ofh, humus A, transition A/B or mineral B. The samples contained mainly single soil horizons (Ofh, A or B). In order to achieve diversity in physical properties, some samples were collected in such a way that they contained horizons Ofh and A or A and B.

Soil monoliths were sampled using the method proposed by Kucza (2003a), by cutting them with metal frames in the shape of prisms with an area of 324 cm^2 and a height of 12 cm. These were cut by pressing the frames vertically from the surface. Soil samples were obtained in the same way; they were collected to cylinders with the diameter of 15 cm and the height of 3, 4, 6 or 9 cm.

2.3. Laboratory tests

2.3.1. Capillary capacity

The measure of water storage capacity of the surface layers of forest soils assumed in the present study was capillary capacity P_k (mm H_2O in a soil layer with the thickness of 1 cm), corresponding to their capillary porosity. The expression of the water storage capacity of soil in balance units enables its direct use in the calculation of water balance, whose components (precipitation, evapotranspiration) are also expressed in such units (Ilek et al., 2015). According to the results, obtained by Kucza and Urbaś (2005), on the water absorption of organic matter relative to the degree of decomposition, individual particles of organic matter need several days to reach the state of maximum filling with water. Therefore, capillary capacity P_k for each soil sample and monolith was determined after placing them in a container with water for a period of 10 days, wherein in the initial stage of soaking (2–3 days) the monoliths and the samples were slowly filling with distilled water by gradual raising the water level in the containers.

After removing the samples and monoliths from the water, they were allowed to drain, which lasted - depending on the nature of the sample and the monolith - from 4 to 12 h, and their mass was determined. Then, the monoliths and the samples were separated according to the scheme presented in the study by Ilek et al. (2015), in order to determine the physical properties, the degree of decomposition, capillary capacity and degree of saturation of individual soil horizons of which they were composed.

Capillary capacity P_k (mm H_2O in a soil layer with the thickness of 1 cm) of different soil horizons was calculated according to the general formula:

$$Pk = (v/V) \cdot 10 \quad (1)$$

where: v is the water volume (cm^3) calculated (assuming the water density of 1 $g \cdot cm^{-3}$) from the difference between the mass of a given soil horizon in the state of maximum water storage capacity and the dry mass of that horizon, determined after its drying in the temperature of 105 °C; V is the volume of a given horizon determined in the state of maximum water storage capacity (cm^3).

As the research concerned mountain forest soils, often containing significant amounts of rock fragments and root systems, it was assumed that all relationships analysed in the present study would only include the fine earth fraction (<2 mm) of A, A/B and B horizons. Therefore, those horizons were washed using a 2 mm sieve. This allowed for determination of the mass of the rock fragments and the roots, corresponding to their maximum water storage capacity,