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Subsurface accumulation of $CaCO_3$ and Cl^- from groundwater under black locust and poplar plantations

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Abstract When conditions are similar, more water evaporates from forest plantations than herbaceous vegetation, thereby affecting hydrological fluxes and ion transport in the soil. The vertical distribution of $CaCO_3$ and Cl^- ions shifts due to afforestation. The effect of groundwater depth and clay content were studied in the Great Hungarian Plain where forest area has been increasing for decades by analyzing soil and groundwater samples from stands of black locust (*Robinia pseudoacacia*, 11 plots) and poplar (*Populus* spp., 11 plots). All study sites contained one herbaceous (control) and one or more forested plots. $CaCO_3$ and Cl^- ions accumulated in the soil profile in greater quantities under tree cover than in the controls. The scale of this process largely depended on the species and on soil and ion properties. Under black locust, Cl^- accumulated between 1.3 and 6.3 m, with a maximum difference of 0.3 pCl unit (pCl is Cl^- activity, the negative of the logarithm to base 10 of the concentration of the chloride ion, determined using an ion-selective electrode, it is a dimensionless quantity.), while the difference in $CaCO_3$ accumulation was at most 3.5% in some layers, compared to control plots. This result may be explained by the difference in the mobility of Ca^+ and Cl^- ions. Different mechanisms were noticeable under poplar plantations due to their higher water uptake: Cl^- accumulation was detected below 0.9 m to the groundwater with a maximum difference of 0.5 pCl units, while $CaCO_3$ accumulation was continuous at depths of 2.3–6.8 m with a maximum difference of 8.4%, compared to the controls. With increasing

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clay content, there was a discernible effect on $CaCO_3$ and Cl^- accumulation under black locust, but not observed under poplars. These differences were explained by the differences in water uptake mechanisms and root patterns of the two species and the different mobility of Ca^{2+} and Cl^- ions.

Keywords Tree plantations · Ion accumulation · Water regime · Water uptake strategy · Root structure

Introduction

The effect of forests on groundwater is well researched, and forests are known to transpire more than herbaceous vegetation due to greater transpiration and evaporative surface areas and deeper root systems (Calder 1998; Nosetto et al. 2005), which can cause local groundwater depression (Major 2002). According to George et al. (1999), this phenomenon appears < 10–30 m from the forest edge when the forest is large enough, but with extensive afforestation projects significant changes can also occur on a regional scale (Lu et al. 2016). This effect on groundwater may be crucial for forest growth or survival depending on local factors (Naumburg et al. 2005) and could induce changes in plant physiology (Gao et al. 2017) and in soil properties (Xia et al. 2016a, b).

Changes in vegetation cover are also known to influence the movement of dissolved ions in the groundwater. Trees accumulate salt by altering hydrological conditions (Heuperman 1999; Nosetto et al. 2007, 2008), and this accumulation can be excessive (Jobbágy and Jackson 2007).

A significant increase in forested areas is planned for Hungary, supported by the European Union (Andrasevits et al. 2005). This goal will be met mainly by land cover changes on poor croplands in the Great Hungarian Plain (Führer and Járó 2005). The annual climatic water deficit is 100–250 mm in this area (Pécsi 1989), increasing by 0.3–0.6 mm yearly due to global climate change (Weidinger et al. 2000). Furthermore, forests require groundwater to survive long periods of drought (Ijjász 1939). Consequently, long-term changes in land use on such a large scale require investigation on the possible effects on water resources and soils.

The Carpathian Basin, which includes the Great Hungarian Plain, lies in a transitional area between the continental, oceanic, and Mediterranean climate zones, and geological conditions are diverse. As a result, the Great Hungarian Plain has been a mosaic-like heterogeneous area since the end of the Quaternary (Sümegi et al. 2002). Heterogeneity has also been increased by human activities (e.g., long-term cultivation, large-scale water management operations, forest plantations), and the factors influencing the research topic (soil texture, level and chemical composition of the groundwater, composition of forests) are highly variable. The transitional nature of the area is shown by the regional occurrence of loess-derived calcareous soils in the more-continental southeastern Great Hungarian Plain, compared to the typical noncalcareous soils of the more humid western areas. In these circumstances, the concentration of shallow-deposited calcium carbonate ($CaCO_3$) might serve as an indicator of leaching/accumulation processes, including evapotranspiration.

Therefore, several well-defined combinations of factors were examined to ensure the practical usefulness of the results. Two main soil texture categories (loam, sand) and two main plantation species were studied, black locust (*Robinia pseudoacacia* L.) and poplar (*Populus* spp.). Black locust has an important role in Hungary as the main species in marginal habitats (Rédei et al. 2011).

Easily and measurable soil variables were used: hygroscopicity (the percentage water in an atmosphere of 35% relative humidity, a definable variable used to indicate soil clay content with threshold values of 0.5, 1, 2, 3.5, 5% for sand, loamy sand, sandy loam, loam and clay loam, respectively), soil $CaCO_3$ content and pCl.

The following hypotheses were examined with these parameters: (1) Trees have greater water uptake than herbaceous vegetation due to their increased transpiration; therefore, plantations create $CaCO_3$ and Cl^- accumulation through soluble ion transport in the soil. This results in the formation of accumulation peaks in $CaCO_3$ and pCl curves of the soil profile. (2) The water uptake mechanisms of the two species are different; thus, their root systems and ion accumulation processes also differ. Poplar has a higher water uptake rate and generates greater ion accumulation peaks, while the peaks are smaller with black locust. (3) These processes are influenced by soil texture, the connectivity between tree roots and the groundwater, and the behavior of $CaCO_3$ and Cl^- ions in the soil. Coarse soil texture, direct root–groundwater connection and ions with higher mobility are factors that increase the possibility of ion accumulation.

The mechanisms described are only valid for well-defined factor combinations, and the results are expected to provide information for forest managers about the ecological and economic consequences of given decisions.

Although many articles on this topic describe the accumulation processes in detail, few studies have been made on the effect of soil texture. Differences between the water uptake by different plants can be better understood when this factor is taken into account. The question of rooting depth and distribution is closely connected to this topic. Although there is very limited direct data are available on root systems of these species in this area (Szodfridt and Faragó 1968), the conclusions could complement the results of rooting depth models based on global-scale databases.

Research on correlations between subsurface $CaCO_3$ accumulation and forests could provide answers on the role of this subprocess in the global carbon cycle. Although this was not the main focus of the work, it could suggest new directions for further research.

Methods and materials

The main factors in forest–groundwater relationships on the Great Hungarian Plain-tree species, stand age, soil texture, groundwater level and groundwater salt content—were taken into consideration when selecting the study sites. Based on the research plan, 108 boreholes were made on 37 sites (Tóth et al. 2014). Each site consisted of a control point with herbaceous vegetation and one or more related forest points, each > 50 m from the forest border to avoid edge effects.

Soil samples were collected at depths of 0–20, > 20–40, > 40–60, > 60–80 and > 80–100 cm, and every 0.5 m below 1 m. The $CaCO_3$ content (using a Scheibler type calcimeter), pCl (the negative of the logarithm to base 10 of the concentration of the chloride ion, determined using an ion-selective electrode) and hygroscopicity value were measured from the samples.

Vegetation cover, tree biomass and groundwater salt content were recorded as supplementary data when boreholes were made.

The hygroscopicity value, i.e., the hygroscopic water content of a soil sample at a certain atmospheric relative humidity (RH), was measured at RH = 35% according to Di Gléria et al. (1962). Verstraeten and Livens (1971) considered this method more reliable for subdividing different soils of a given texture than the more classical granulometric analysis. Wuddivira et al. (2012) found a linear dependence between clay percentage and hygroscopicity values at RH = 50%. The groundwater level was recorded and samples collected at every site for chemical analysis. In each case, the total borehole depth was the groundwater level observed during boring plus 1 m to a maximum of 11 m.

Boreholes were chosen for further investigation where clear accumulation peaks occurred in the $CaCO_3$ and pCl curves of the soil profile compared to the curves at the control points, and the distance between the $CaCO_3$ and pCl peaks was not more than 1 m in depth. Points where the $CaCO_3$ curves differed greatly from the control point curves, presumably due to the different geological layering, were excluded. Furthermore, there were some control points where ion accumulation peaks could not be unidentified due to the great fluctuation in depth. Forest points without clear ion accumulation peaks were also excluded from the analysis as were sites where the distance between the forested and control plots was more than 500 m. The use of these conditions made it possible to eliminate sites with heterogeneous geological layering.

The basic data of the chosen sites and data on ion accumulation peaks are summarized in Appendix S1. Eleven stands each of black locust and poplar were chosen. Correlations between the depth of the $CaCO_3$ and pCl accumulation peaks, groundwater levels and hygroscopicity values were analyzed with correlation analysis using SPSS software version 17.0 (SPSS, Chicago, IL, USA).

At one site, where groundwater data were available for a poplar stand (point 126) and the herbaceous vegetation (point 124) over a period of 105 and 84 days, respectively, daily evapotranspiration was estimated from diurnal groundwater fluctuations according to Gribovszki et al. (2008). The results of this estimation are not representative of all the sites, but provide useful supplementary information on the given conditions.

Results

Effect of different tree species on groundwater levels, ion accumulation and pH under tree plantations

Although the groundwater uptake recorded for poplar (3.38 mm/day) was significantly less than that reported by Szodfridt (1993) (3.71 mm/day), it was still higher than that measured at the control points (1.29 mm/day), confirming the conclusion drawn by other authors on the higher evapotranspiration produced by tree stands.

The average $CaCO_3$, pCl and pH curves of the tree-covered and control plots are presented in Fig. 1. For ease of interpretation, these curves were transformed into difference curves ($\Delta CaCO_3$, ΔpCl and ΔpH) in Fig. 2.

Compared with the average $CaCO_3$ content of the soil profiles, $CaCO_3$ accumulation was only observed under poplar, being much less pronounced under black locust (Figs. 1a, 2a). Quite different patterns were found with Cl^-, as an accumulation layer (i.e., lower pCl) was found under both poplar and black locust (Figs. 1, 2b), indicating that the species and the type of ion both affect ion accumulation dynamics. As expected, acidification of the forested plots was observed for both species compared to the controls due to root functions and leaching (Figs. 1, 2c). There was greater acidification under black locust, possibly due to nitrification (Montagnini et al. 1991), which inhibits $CaCO_3$ accumulation only below the main root mass in the capillary or saturated zone.

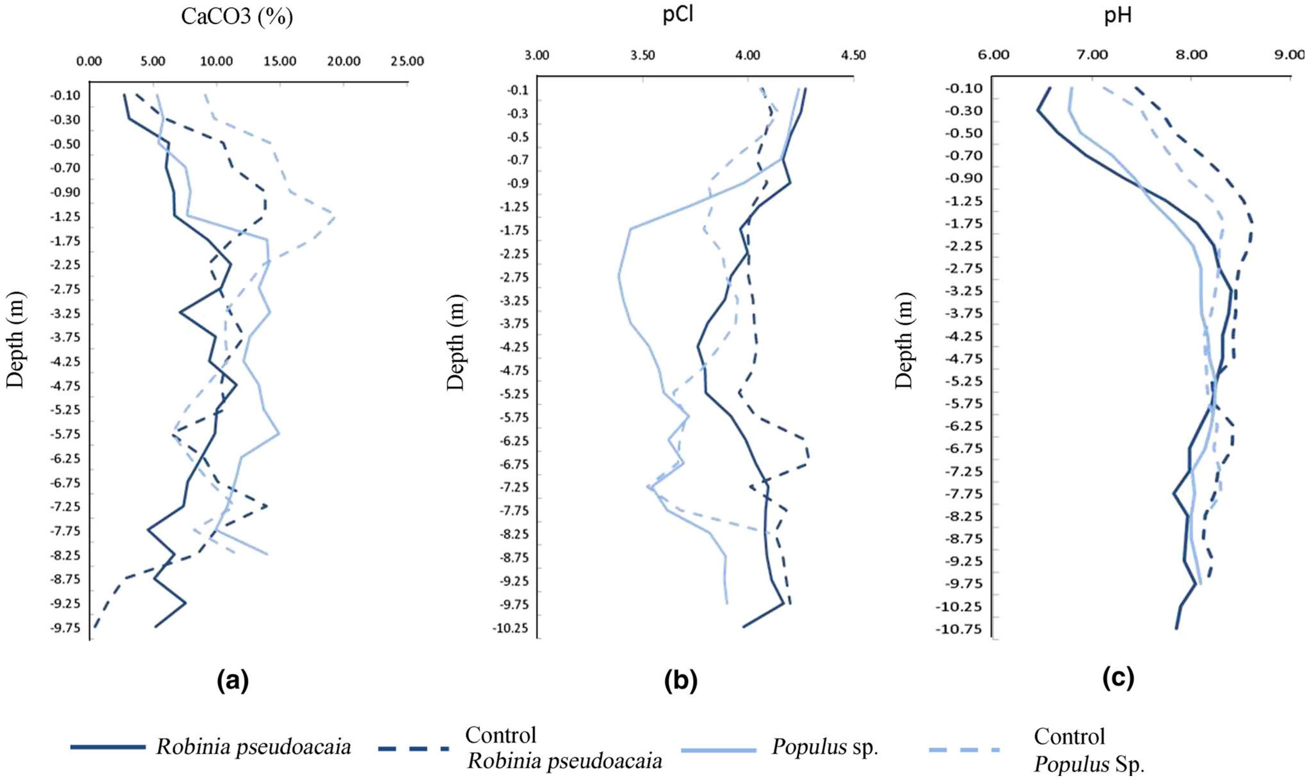

Fig. 1 Average $CaCO_3$ (**a**), Cl^- (**b**) and pH (**c**) curves under black locust, poplar and the corresponding control points

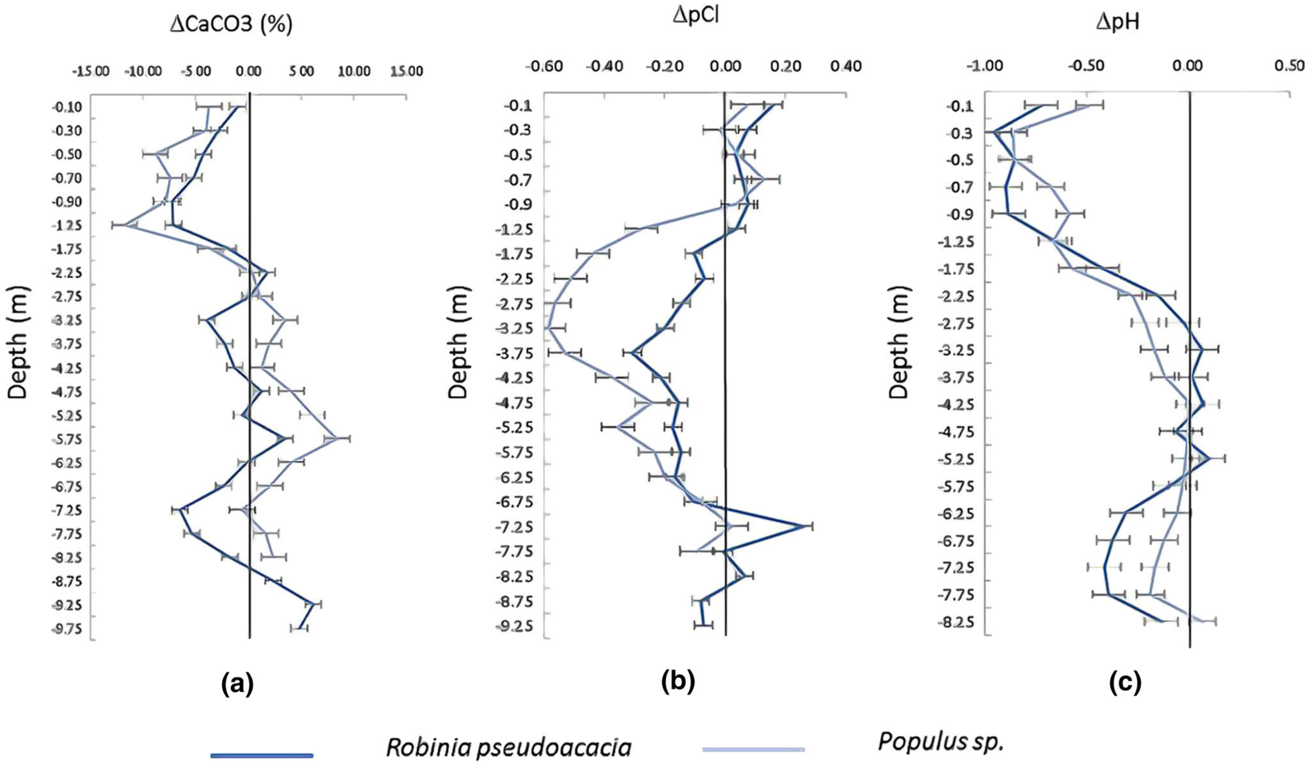

Fig. 2 Average $CaCO_3$ (**a**), Cl^- (**b**) accumulation and acidification effect (**c**) under black locust and poplar (values at forested points minus values at control points). Positive values show $CaCO_3$ accumulation (**a**), while negative values show Cl^- accumulation (**b**) or acidification (**c**) compared to the control point ($n = 11$ black locust and 11 poplar stands)

No significant correlation was found between the absolute rates of $CaCO_3$ and Cl^- accumulation, which could be due to the greater geological variability of the Great Hungarian Plain compared to the Pampas (Jobbágy and Jackson 2007). Therefore, the absolute accumulation under forest and control points could not be compared in the present case.

There was a clear difference between $CaCO_3$ accumulation under black locust and poplar (Fig. 2a). Under black locust, there was only a weak accumulation in some layers, with a maximum difference of 3.5% between the forest and control plots. Under poplar, however, there was a continuous accumulation from of 2.3–6.8 m with a maximum difference of 8.4% $CaCO_3$ content (Fig. 2a). The main factor behind this difference was the diverse water uptake of the two species: black locust primarily makes use of soil moisture through capillaries, depending on the meteorological conditions, and has no direct effect on groundwater or dissolved ion transport. The main process in the root zone is soil moisture fluctuation, depending on precipitation and water uptake, which are not associated with massive ion transport. Therefore, there is no significant ion accumulation.

In contrast, water uptake by poplar is directly from the groundwater, so ion transport is possible even from greater distances. $CaCO_3$ clearly accumulated under poplar stands, depending on the groundwater level and moisture regime of the soils.

Effect of difference in solubility and adsorption between $CaCO_3$ and Cl^- ions

Most of the chloride salts in the soil and geological layers are highly soluble. Consequently, in contrast to the pattern of the $CaCO_3$ depth curve, Cl^- accumulated even under black locust between depths of 1.3–6.8 m, with a maximum difference of 0.3 pCl unit (Fig. 2b), due to the higher solubility of Cl^- ions in groundwater. Moreover, chloride ions are not adsorbed on negatively charged soil particles, so they accumulate even when water transport is less pronounced. Nevertheless, the rate of accumulation generated by black locust was less than by poplar, where accumulation was continuous from 0.9 m with a maximum difference of 0.5 pCl unit (Fig. 2b).

Effect of texture on ion accumulation differences under tree plantations

The study sites could be divided into two clearly defined groups according to soil texture. Although both contained more than two soil texture categories, one can be referred to as sandy (sand and loamy sand categories; with maximum hygroscopicity values of 0.8 under black locust and 0.7 under poplar), and the other as loam (sandy loam, loam and clay loam categories; with minimum hygroscopicity values of 1.5 under black locust and 2.5 under poplar).

Accordingly, further analyses were carried out in three groups for both tree species for all the chosen points together and for loam and sandy soils separately.

The influence of soil texture was clear for both species, but to different extents. Water movement was faster, soil moisture changed more suddenly, and the solid phase of the soil adsorbed fewer dissolved ions in the sand group. This result meant that accumulation layers could be formed when there was less water movement and could explain the $CaCO_3$ accumulation under black locust (Fig. 3a).

Ion movement and moisture change are much slower in the case of loam soils, and more water is needed to form an accumulation layer. The rate of accumulation was therefore lower in the loam group than in the sand group of soils, although it might be concluded that poplar resulted in $CaCO_3$ accumulation regardless of soil texture (Fig. 3a, b).

Correlations between the depth of accumulation peaks and other factors

Black locust

There were significant correlations between the depths of the accumulation peaks (m) and groundwater levels (m) ($R = 0.635$; $p < 0.05$; $n = 11$), and also between the depths of the accumulation peaks (m) and the average hygroscopicity at all depths ($R = -0.592$; $p < 0.05$; $n = 11$; average hygroscopicity value between surface and groundwater; $R = -0.594$; $p < 0.05$; $n = 11$; average hygroscopicity value in the 1 m layer; $R = -0.545$; $p < 0.05$; $n = 11$; average hygroscopicity value between 1 m and the groundwater). These results show that soil texture and groundwater levels also influenced the depth of the accumulation peaks and possibly also the depth of the root zone.

Groundwater was 1.5–5.4 m below the accumulation peaks in all cases. Assuming that the peaks indicate the bottom of the root zone, the roots of black locust may be presumed to rarely reach the groundwater. Therefore, the effect of the groundwater level is shown through capillary action. In the case of black locust, a strong correlation was found only for sandy soils between the depths of the accumulation peaks and the average hygroscopicity ($R = 0.99$; $p = 0.01$; $n = 6$; average hygroscopicity determined between 1 m and the groundwater level). The distance between the accumulation peaks and groundwater increased with increasing hygroscopicity. Thus, the finer texture of the sand subsoil led to shallower accumulation peaks under black locust than at sites with coarser textures. There was no such correlation with clay soils or poplar.

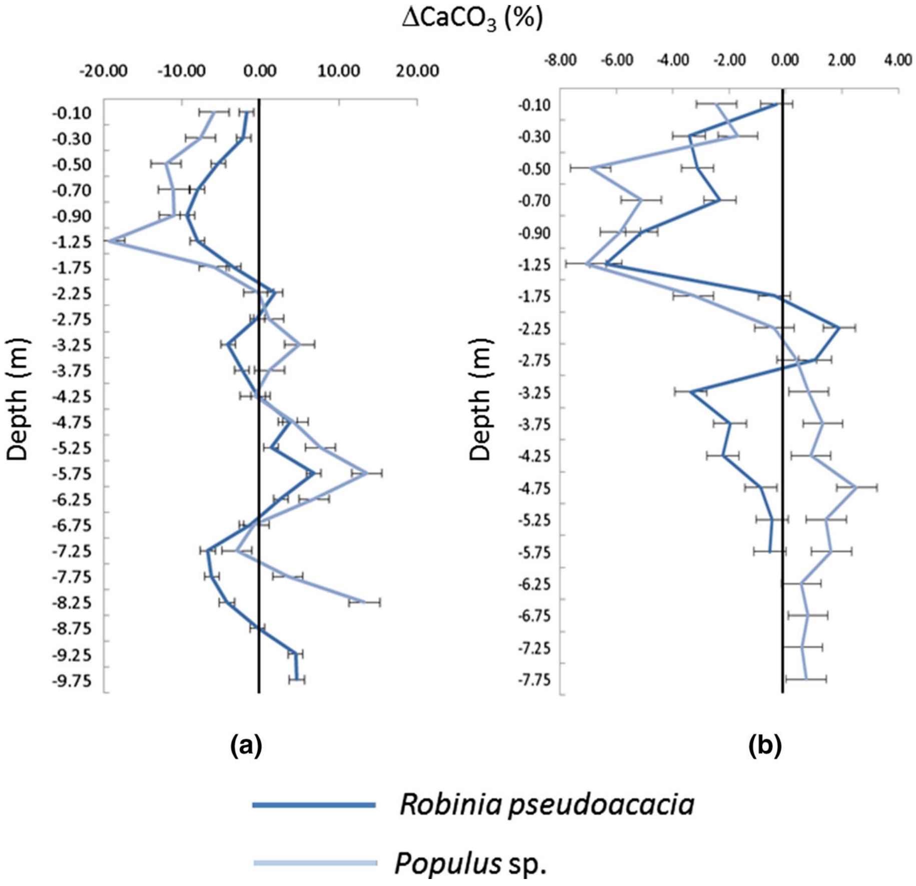

Fig. 3 Average $CaCO_3$ accumulation under black locust and poplar ($CaCO_3$% values at forested points minus those determined at control points) in the sand (**a**) (black locust $n = 5$; poplar $n = 5$) and loam groups of soils (**b**) (black locust $n = 6$; poplar $n = 6$). Positive values show $CaCO_3$ accumulation compared to the control point at the indicated depth

These results indicate that, if the sandy soils have better water regime properties (relatively smaller particles) above the groundwater level, the roots require less effort to reach the groundwater.

The root system of black locust also responded to soil texture and groundwater levels, but the response was less evident on loamy soils. This result may be explained mainly by differences in water movement in sand and in loam: the processes of infiltration, surface evaporation and capillary rise are more rapid on sand although the latter is limited. Trees on sandy soils try to take up the infiltrating water near the surface as soon as possible. However, in periods without rain, the coarse sand rapidly dries out, and the roots have to reach the capillary zone to satisfy the water needs of the tree. For this reason, the root mass of black locust changes more sharply with depth in sandy soils than in loam, where soil moisture moves more slowly and field capacity is greater (Fig. 4a).

Poplar

For the poplar stands, there was a significant correlation between the depths of the accumulation peaks (pCl, $CaCO_3$) and the groundwater ($R = 0.810$; $p < 0.05$; $n = 11$), but there was no significant correlation between groundwater levels and other abiotic factors. The level of the groundwater was the main factor under poplar stands determining the bottom of the root zone. The accumulation peaks were located above the groundwater as with black locust, but the difference was less (0–2.9 m, with the exception of point 2, where a significant drop in the groundwater has been observed in recent decades). This distance between accumulation peaks and groundwater depth was not influenced by soil texture, in contrast to the black locust stands. Since soil samples were taken in late summer at maximum groundwater depth, it may be assumed that the roots reached groundwater and satisfied their water requirements (Móricz et al. 2016a, b) (Fig. 4b).

Discussion

According to the general rule expressed by Schenk (2008), plants try to keep their roots as shallow as possible but penetrate as deeply as necessary, depending on their water needs and water available. This provides a reasonably accurate explanation of the present results. The water requirements of poplar are 2.5 times greater than those of black locust (Járó 1981), and the latter is able to satisfy

Fig. 4 Hypothetical root distribution of black locust (**a**) and poplar (**b**) with the most important factors of water uptake. Normal arrows: important factors; dashed arrows: less important factors; thick arrows: fast water movement; thin arrows: slow water movement

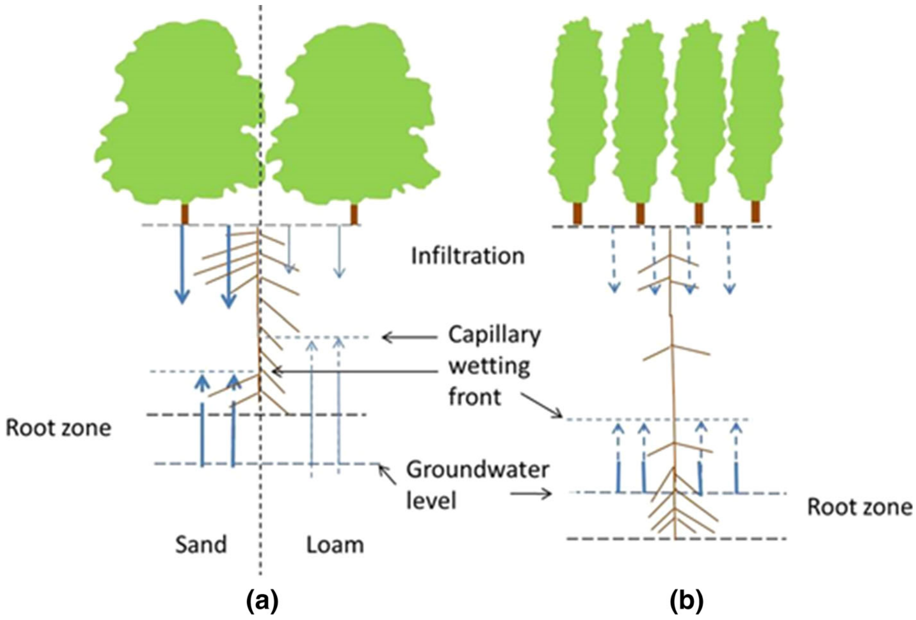

Table 1 Accumulation patterns under each tree species and their connection with the influencing factors: − no accumulation/effect, + accumulation/effect, ++ strong effect

Tree species	$CaCO_3$ accumulation (average of all study sites)	Cl^- accumulation (average of all study sites)	Effect of groundwater depth	Effect of soil texture
Black locust	−	+	− (+ on sand)	++
Poplar	+	+	++	−

them primarily from infiltrating precipitation in the Great Hungarian Plain.

Black locust mainly takes up soil moisture from within a depth of 1 m. However, on coarse sandy soils with limited water storage during dry periods, the species is forced to use the capillary water moving upwards from the groundwater. This periodical change in the water uptake mechanism agrees with the results of earlier studies on other tree species (Priyadarshini et al. 2015) and also on black locust (Rickard and Price 1989), although these studies did not investigate the role of soil texture. In the present study, the higher clay content, and consequently the better water regime properties, allowed the development of a less differentiated root system, and greater independence from groundwater resources. According to Wu et al. (2015), plants develop different phenotypes in order to control their transpiration and are more vulnerable to unfavourable climatic conditions (e.g., drought) on sandy soils. The results show that this kind of adaptation is also valid for water uptake mechanisms.

Poplar, however, uses the groundwater as its main water source due to its high water demand. Although different values have been reported for the magnitude of groundwater use, there is consensus about the direct groundwater use of this species (Wilske et al. 2009; Snyder and Williams 2000). Moreover, these trees show no response to soil moisture changes in shallower soil layers (Cox et al. 2005). Therefore, the root system of poplar is not as differentiated as that of black locust.

The variation in annual growth dynamics is another sign of the different water uptake mechanisms of the two species: the leaf-catalase enzyme curve for black locust begins with a steep increase during maximum precipitation (April–May), while the activity for poplar lasts longer and is more balanced (Szendrey and Juhász 1969). This finding suggests that poplar species are relatively independent of precipitation since they use mainly groundwater, while black locust has developed the opposite strategy.

These significant differences also explain the results for $CaCO_3$ and Cl^- accumulation. There was no significant $CaCO_3$ accumulation with black locust due to the absence of a direct root–groundwater connection, leading to poor $CaCO_3$ transport.

However, Cl^- ions accumulated because they are not adsorbed to soil particles (White and Broadley 2001). Hence, their movement is determined by water movement (Tisdale et al. 1985), and they move in the soil more easily at lower water flux. Accumulation zones of Cl^- are therefore more likely to form under these conditions, confirming the conclusion that there is only an indirect connection between the root system of black locust and groundwater via soil capillaries. In contrast, there is substantial $CaCO_3$ and Cl^- accumulation under poplar stands due to the direct root–groundwater connection, which generates continuous ion movement toward the roots.

These observations agree with the salt-accumulation model of Jobbágy and Jackson (2007).

Conclusions

Although we can concluded that water uptake by plants results in salt accumulation, this process is strongly affected by the type of root–groundwater/soil moisture connection and by factors affecting the movement of particular ions in the soil (e.g., texture, movement of groundwater, soil moisture).

The effect of texture is stronger when the roots have no direct connection with the groundwater. Water uptake is thus determined by the water regime properties of the soil or capillary rise from groundwater. These properties depend primarily on soil texture.

The results indicate that water uptake mechanisms under black locust and poplar are not the same, and therefore the type of accumulation by these species is significantly different. The main points of the study are summarized in Table 1.

Under black locust, no $CaCO_3$ accumulated, but Cl^- accumulated due to its greater mobility in the soil. The effect of groundwater depth was only observable on sandy soils since trees are more dependent on groundwater on this type of soil. However, the effect of soil texture is clear. As a medium between water and the roots, it determines ion movement as well.

Under poplars, these mechanisms are simpler. Due to their greater water requirements, this species results in both $CaCO_3$ and Cl^- accumulation. The roots are in close contact with the groundwater table so the effect of groundwater is crucial. For the same reason, the effect of the soil as a medium is negligible. The results confirmed the model previously formulated for the influence of root systems and species on salt movement (Tóth et al. 2014); however, the species and soil texture have also proven to be important factors in tree-water systems.

It could be important for forest managers to know that species that use groundwater directly have a high chance of generating salt accumulation in the root zone. This process is likely to be more intensive on coarse sandy soils and should be taken into account, especially in areas where the salt content of the groundwater is high and where salt accumulation could cause significant economic losses. Digital habitat databases (Illés et al. 2006) will help to identify such areas.

It can be assumed that ion accumulation has a long-term effect on the growth and health of trees. Further research is therefore planned on the correlations between stand age and the process of accumulation (quantity, time scale).

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