Article

The Impacts of Vineyard Afforestation on Soil Properties, Water Repellency and Near-Saturated Infiltration in the Little Carpathians Mountains

Andrej Hrabovský¹, Pavel Dlapa^{1,*}, Artemi Cerdà² and Jozef Kollár³

¹ Department of Soil Science, Faculty of Natural Sciences, Comenius University, Mlynská Dolina, Ilkovičova 6, 842 15 Bratislava, Slovakia; andrej.hrabovsky@uniba.sk

² Soil Erosion and Degradation Research Group, Department of Geography, Valencia University, Blasco Ibáñez 28, 46010 Valencia, Spain; artemio.cerda@uv.es

³ Institute of Landscape Ecology SAS, Štefánikova 3, 814 99 Bratislava, Slovakia; j.kollar@savba.sk

* Correspondence: pavel.dlapa@uniba.sk; Tel.: +421-2-9014-9574

Received: 9 August 2020; Accepted: 11 September 2020; Published: 12 September 2020

Abstract: Vineyards are a 7000-year-old land-use tradition and both management and abandonment have result in altered soil properties. These have a great effect on water resources and soil services, and this inspired our investigation into the effects of land-use and land-use change on soils in the Modra wine-growing region in South-western Slovakia. Ten topsoil samples were taken at each of the seven research sites ($n = 70$) on granite parent material in cultivated and afforested vineyards and original forest soils. Laboratory analyses included determination of soil texture, organic carbon content, soil pH, and water repellency. This was supplemented by infiltration measurements under near-saturated conditions at the vineyard and afforested study sites. Studied soils have a low clay content and a high proportion of sand. The vineyard soils have significantly higher pH than the forest and afforested soils because the naturally acidic soils have been limed. The forest and afforested soils have similar properties, with higher organic carbon content. This makes them strongly to extremely water repellent and contrasts sharply with the wettability of cultivated vineyard soils. One afforested site, however, was less acidic and therefore was considered transitional between forest and vineyard soils. Our infiltration measurements established the influence of soil water repellency on the infiltration process, and our results highlighted that the infiltration rate in the vineyard soils was significantly higher than in afforested soils. The infiltration rate also gradually increased over time in afforested soils due to decreasing water repellency. Physically impossible negative sorptivity values in afforested soils were noted because of changes in water repellency during the infiltration process. Finally, we conclude that soil afforestation results in increased soil water repellency and a subsequent reduction in the infiltration rate at the matrix scale.

Keywords: soils; land-use; vineyards; afforestation; water repellency; infiltration

1. Introduction

Soil has a crucial influence on matter and energy cycles, and knowledge of these cycles is most important in understanding the Earth's surface geography. Rodrigo-Comino et al. [1] highlighted the interconnection between different geographical spheres and Keesstra et al. [2] reported that soil systems provide ecosystem services and determine the Earth's hydrological, erosional and biogeochemical cycles.

Most recently, Visser et al. [3] emphasized the importance of soil in sustainable development and in implementing strategies which achieve land degradation neutrality. The United Nations has also stressed that soils are relevant in achieving its Sustainable Goals initiative, and soil scientists have

accepted the associated challenges. Scientific work is now influencing land managers, politicians, practitioners, end-users, and other scientific disciplines in acknowledging that soils are a key component of the Earth's function and thus are crucial for human sustainability [4].

The fate of soil water and carbon is most important because of their effect on the water cycle and climate change [5,6]. Current research shows that relevant soil processes are fundamentally influenced by land-use and land management because soils constitute the first earth system affected by humans in agriculture, grazing, mining, and infrastructure development [7–9]. Land-use is also very dynamic due to continuous global activity and technological innovation, and resultant farming, grazing, transport, industry, tourism, mining, and other economic activities affect the Earth's surface [10–12].

There is also frequent deforestation and transformation of forests into agricultural land in the tropics and subtropics [13–17]. In contrast, developed economies often abandon cultivated agricultural land for settlements and industry or return it to grassland and forest [18–20]. This abandonment results in altered soil properties on the long and medium-term scale [21,22], and it inevitably changes soil–water interaction. This applies especially to infiltration rates [23–25], reduced water runoff and soil erosion [25,26].

The transformation of agricultural land into forest land or grassland continues in many parts of Europe. This is particularly noticeable in transformed economies in Eastern Europe, where existing agricultural land-use in many places became increasingly unprofitable in the early 1990s, following the demise of cooperative farming. This process proved disastrous for water runoff, solute output [27], and mountain management in Mediterranean Europe [28].

This trend is especially important in areas where soils are less fertile and more susceptible to degradation from compaction or erosion and there is accompanying low agricultural profitability and rural emigration [29,30]. In addition, bare soils without vegetation cover are highly susceptible to increased compaction, surface runoff, and erosion [31]. The arable soils in these regions can therefore be converted into grasslands, subjected to planned afforestation, or left to natural re-vegetation [32–34]. All these changes result in altered runoff discharge, sediment availability, and landforms [35–37].

At the turn of the 19th and 20th centuries, many pests ravaged vineyards throughout Europe. For example, the *Phylloxera vastatrix*, *Plasmopara viticola*, and *Uncinula necator* species altered vineyard use in Slovak wine-growing regions. Resultant dramatic changes in land-use are also linked to the economic and social conditions in particular countries and their climate conditions. Thus, the pest attacks and the social changes in Slovakia from 1949–1953 changed many vineyards into other land-uses. It has been well established that land-use changes have a great impact on soil properties and processes [38–40], and it is therefore necessary to assess these effects on individual soils.

One of the most significant consequences of changing arable land to pasture or forest is increased soil organic matter content [41–47]. The soil organic matter is primarily responsible for changes in soil wettability, and many authors have established a strong correlation between soil organic matter content and soil water repellency [48–51]. These water repellent soils have a soil-water contact angle $\varphi > 90^\circ$. In addition, the impact of water repellency on soil processes is well-described in the literature [52–54], because it typically decreases infiltration rate [55,56] and then influences preferential flow [57,58].

This paper investigates the impact of afforestation and vineyard cultivation on soil properties. Soils converted to forests over the last century are compared with those used in vineyards, with special emphasis on the effects of land-use on the soil properties, the susceptibility to water repellency development, and the impacts of agriculture land abandonment.

2. Materials and Methods

2.1. Study Sites

The study area is situated on the south-eastern slopes of the central part of the Little Carpathians mountain range in the surrounds of the Modra Township in south-western Slovakia. The soils here developed from granitic rocks and they are classified as Haplic Cambisols (Dystric) under

the International Union of Soil Sciences (IUSS) Working Group World Reference Base (WRB) [59]. The mean annual air temperature is 6 °C–8 °C [60] and the annual precipitation is 600–700 mm [61]. The original forests have a tree and shrub layer dominated by oak (*Quercus petraea* agg.) and hornbeam (*Carpinus betulus*), and a herb layer composed of forest mesophytes. On the other hand, the tree layer in the afforested vineyards is dominated by oak (*Quercus petraea* agg.) and the herb layer comprises both forest mesophytes and nitrophytes (synanthropic species). The forests on the sites of former vineyards have formed spontaneously over the last 100 years. Finally, the vineyard soils have variable segetal vegetation, traditionally classified in the *Veronico-Euphorbion* Sissingh ex Passarge 1964 alliance. The sampling sites are listed in Table 1 and a view of the different land-uses is shown in Figure 1.

Table 1. Study site locations and land-use around Modra Township in Western Slovakia.

Study Site	Latitude	Longitude	Land-Use
F1	N 48°20′36.3″	E 17°17′01.7″	original forest
F2	N 48°20′35.5″	E 17°17′09.2″	afforested vineyard
F3	N 48°19′41.8″	E 17°16′43.7″	original forest
V1	N 48°20′26.2″	E 17°17′26.3″	vineyard
V2	N 48°18′56.2″	E 17°16′54.1″	vineyard
V3	N 48°18′53.0″	E 17°16′58.3″	vineyard
TF	N 48°19′23.1″	E 17°16′50.3″	afforested vineyard

Figure 1. Left to right: the vineyard, afforested, and forest plots.

2.2. Field and Laboratory Methods

Ten random soil samples were taken at a depth of 0–10 cm from 20 × 20 m² plots at each study site. Gravel and plant residues were removed before laboratory analysis, and samples were gently ground to pass through a 2-mm sieve. Soil pH was established at a 1:2.5 soil/distilled water ratio (*w/v*). Particle size distribution was then determined by measuring the amount of soil particles in suspension after various settling times and the fraction size percentage was determined by the pipette method [62]. Finally, soil organic carbon content was determined by potassium dichromate oxidation [63].

The persistence of water repellency in all samples was estimated by the widely used water drop penetration time test (WDPT) after two-week equilibration at 20 °C and 50% relative humidity. The measured WDPT values gave the following soil classifications [54]: wettable soils (<5 s), slightly water repellent (5–60 s), strongly water repellent (60–600 s), severely water repellent (600–3600 s), and extremely water repellent (>3600 s).

Four replicated infiltration experiments were performed in the vineyard and afforested research sites using a Mini Disk Infiltrometer (Decagon Devices, Inc., Pullman, WA, USA). This was set to

a -2 cm supply pressure-head and filled with water. The time required to infiltrate each cm^3 of water was recorded and the cumulative infiltration dependence was determined by regression Equation (1):

$$I = C_1 t^{0.5} + C_2 t, \quad (1)$$

where I is the cumulative infiltration (cm), C_1 is the constant corresponding to sorptivity S ($\text{cm}\cdot\text{s}^{-0.5}$), C_2 is the constant related to unsaturated hydraulic conductivity ($\text{cm}\cdot\text{s}^{-1}$), and t is the time (s).

2.3. Statistical Analysis

Statistical analysis was performed using the ‘LMFIT for Python’ package [64]. ANOVA and Tukey tests were used to evaluate differences in soil properties in the study plots and the determination coefficient (r^2) was calculated for regression relationships. The WDPT values were evaluated as log-normal. For all statistical tests, the level of significance was chosen as $p < 0.05$.

3. Results

3.1. The Impact of Afforestation on Soil Properties

Average soil pH values vary over a wide range and depend on land-use history (Table 2). The strong acidity in forest and afforested soils is a consequence of natural soil-forming processes on granitic parent rock. Soil organic carbon (SOC) gradually accumulates during soil development, with a concurrent soil pH decrease. Figure 2 highlights a significant indirect relationship between SOC and pH in sites F1, F2, and F3. In addition, the SOC content is significantly higher and the soil pH is significantly lower in forest and afforested soils than in the vineyard soils.

Table 2. Basic soil properties determined in 10 samples at each study site.

Study	pH		SOC (wt.%)		Sand (wt.%)		Silt (wt.%)		Clay (wt.%)		log WDPT	
Site	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
F1	4.05	0.10	8.61	2.35	54.1	4.0	35.0	3.1	10.9	1.6	4.13	0.18
F2	4.58	0.17	5.92	1.86	60.6	3.6	29.6	2.9	9.5	1.0	2.72	0.99
F3	4.33	0.14	5.72	1.73	55.8	3.8	34.6	3.1	9.6	0.9	1.92	0.98
V1	6.04	0.20	0.56	0.16	70.6	2.0	22.8	1.5	6.7	0.6	0.00	0.00
V2	6.95	0.61	1.83	0.50	49.9	3.2	38.9	2.4	11.3	1.1	0.00	0.00
V3	7.52	0.16	2.03	0.14	47.1	2.5	38.2	1.0	14.7	1.9	0.00	0.00
TF	5.67	0.43	7.32	1.16	63.2	2.8	30.7	2.7	6.1	0.9	1.35	0.72

SOC: soil organic carbon content; SD: standard deviation.

The opposite situation occurs in current vineyards. Soil properties there are influenced by the overturning of soil horizons during the vineyard establishment, and the topsoil has very low organic matter content when the humus horizon has been transferred to a greater depth. The topsoil SOC content then gradually increases during cultivation and its pH increases due to liming. Figure 2 therefore shows a close relationship between soil pH and SOC content for sites V1, V2, and V3. The liming induces significantly higher pH than in forest soils and the soil often becomes alkaline (Table 2).

Figure 2 also shows that the TF afforested site samples have specific characteristics. Their chemistry falls in the transition between vineyard and forest soils. Thus, these samples indicate how the chemical properties gradually change following vineyard afforestation and they highlight their gradual acidification. There is an initial recovery of organic matter, that will eventually change the soil water repellency and infiltration rate.

The soil particle size distribution varies widely in the vineyard and forest soils, and the intervals overlap. The sand content dominates the silt content in all soils and the clay content is very low (Table 2). In addition, the V1 re-established vineyard soil has the highest sand content and lowest clay content of all research plots.

Figure 2. SOC content and soil pH relationships in samples collected from vineyards, forests, and afforested vineyards.

3.2. Soil Water Repellency

The persistence of water repellency, determined as WDPT, primarily depends on SOC content. Vineyard soils have the lowest carbon content, and it is not surprising that the V1, V2, and V3 site soils are all wettable.

The forest and afforested soils have varying degrees of water repellency. Figure 3 shows that repellency severity mainly depends on SOC content. The persistence of water repellency was highest in the F1 forest plot, which has 13,600 s mean WDPT, classified as extremely water repellent. The afforested F2 vineyard plot has strongly water repellent soils, with 530 s mean WDPT, and the F3 forest plot has 84 s mean WDPT. The differences between F1, F2, and F3 plots are statistically significant, at $p < 0.05$.

Figure 3. Dependence of persistence of soil water repellency (log water drop penetration time test (WDPT)) on SOC content at the vineyard, forest, and afforested study sites.

The TF afforested vineyard is in a transient stage between vineyard and forest soil. Although Figure 2 shows that the soil pH values are higher than other forest and afforested soils, Figure 3 highlights that the WDPT values are lower than those which correspond to SOC content. The lower than expected soil water repellency is attributed to higher soil pH in the TF study plot than at the other forest and afforested sites.

3.3. Infiltration under Near-Saturated Conditions

Field measurements established that the persistence of water repellency (WDPT) has major impact on infiltration, and Figure 4 shows the infiltration trends. At the V1 vineyard with WDPT < 1 s, the infiltration rate was highest at the start because of the capillary force but this rapidly decreased until it stabilized, which corresponded to the action of gravity under near-saturated conditions (at $h = -2$ cm).

Figure 4. Dependence of infiltration rate (i) on the extent of infiltration (I). The points show the average values of four independent infiltration measurements in the vineyard and afforested research plots.

In contrast, the afforested vineyard TF soils had weak (23 s) mean water repellency, with its lowest infiltration rate at the beginning of the experiment, and this then slowly increased (Figure 4). The infiltration rate was significantly lower than in the vineyard soil. Figure 5 shows the following two trends in the course of infiltration. Cumulative infiltration dependence on time creates a concave curve in the wettable V1 soil and a convex curve in the water repellent TF afforested soil. In addition, the persistence of water repellency was too high to measure the infiltration in the strongly and extremely water repellent soils, at $h = -2$ cm.

Equation (1) was fitted to field infiltration data and the regression equations are listed in Figure 6. The C_1 and C_2 constants from these equations reveal that the TF forest-site water repellency decreased both parameters more than an order of magnitude compared to the V1 vineyard site. The lower diagram in Figure 6 shows that the $S = C_1$ sorptivity had negative values in two instances. Such negative parameter values in Equation (1) are physically impossible and the values suggest that the infiltration course is significantly influenced by changing water repellency, and that infiltration increases when water repellent substances are washed out or removed.

Figure 5. Dependence of cumulative infiltration on time measured at the V1 vineyard site (**upper**) and TF afforested site (**lower**).

Figure 6. The early cumulative infiltration dependence on the square root of time, and the regression models (Equation (1)) fitted to four infiltration measurements at the V1 vineyard site (**upper**) and TF afforested site (**lower**).

4. Discussion

4.1. Impact of Land-Use on Soil Organic Carbon Content (SOC)

The significantly increased SOC content observed after afforestation in the Little Carpathians are listed in Table 2. Kumm and Hessle [65] reported that natural vegetation recovery and afforestation resulted in increased soil organic matter from accumulated biomass and soil formation processes. In addition, Úbeda et al. [66] recorded that a lack of ploughing and vegetation recovery increased soil quality in agriculture terraces in the Capafonts in Catalonia on the Iberian Peninsula. These terraces had been initially abandoned and then subjected to prescribed fires.

Many authors focused their attention directly on the land-use effect upon SOC in soils [67,68]. Arable soils often suffer from a depletion of SOC [69]. However, the conversion of arable soils to pastures causes an increase in SOC [43,44,46]. A decrease in soil erosion and a slower rate of decomposition are responsible for this SOC increase [41,42,47]. The SOC decomposition rate is affected by various factors, such as organic matter composition, soil texture, structure, aeration, and moisture [70]. Changes in SOC content upon land-use changes are related to land-use intensity [71]. Schulze et al. [45] reported increasing average land-use intensities from forest to grasslands to cropland with an increasing harvested fraction of the net primary productivity ($12\% \pm 3\%$, $29\% \pm 8\%$ and $47\% \pm 15\%$, respectively, for Europe). Thus, croplands leave a smaller SOC fraction than forests to build up and maintain SOC stocks [71].

4.2. Impact of Land-Use on Soil Water Repellency

Vineyard cultivation with consequent low organic matter content results in a low quantity of hydrophobic substances in the soil. However, there is a gradual increase in soil organic matter and hydrophobic substances when agricultural soils are transformed into forest or grasslands. Figures 2 and 3, as well as Table 2, show that the dependence of soil water repellency on soil organic matter content is expressed in a WDPT decline along with an SOC decrease in cultivated vineyard soils. This is supported in Seaton et al. [72], and many authors report the close association between organic matter content and soil water repellency [48–51,73–75].

In addition, Capriel [76] concluded that tillage depletes C-H aliphatic units and, implicitly, soil organic matter hydrophobicity, and cultivation therefore results in decreased SOC and less water repellency. Franco et al. [77] then observed reduced water repellency in soils which had long been bare, without vegetation and plant residue supply, and Schnabel et al. [78] recorded a strong negative relationship between soil water repellency and the percentage of soil without plant cover.

In contrast, Doerr et al. [54] reported that some authors have noted only small or insignificant correlation between soil organic matter and soil water repellency [79,80]. Doerr et al. [54] further considered that even a small amount of hydrophobic substances can cause strong soil water repellency, and other authors ascribe the crucial development of water repellency to organic matter quality rather than quantity [81,82]. Despite these conflicting reports, it can be assumed that an increase in carbon content from land-use change affects the physical processes of soil that depend on soil–water interactions, i.e., infiltration, surface runoff, and erosion.

Seaton et al. [72] further reported that arable systems had significantly lower water repellency than all other land-uses, and this was even lower than expected due to their higher pH and lower carbon content. Figure 3 shows that the TF afforested study site is also less water repellent than expected from its SOC content, and this may be due to the effect of its higher soil pH compared to other forest and afforested sites (Figure 2, Table 2). This soil pH effect on water repellency is further recorded by authors including Lebron et al. [83], Mirbabaei et al. [84], and Kořenková et al. [85], and it was also experimentally investigated by Amer et al. [86] and Diehl [87].

The reasons pH affects soil water repellency include the following. The most frequently mentioned influence is protonation and deprotonation of soil organic functional groups such as carboxylics. The protonated carboxyl groups are less hydrophilic than deprotonated groups and this provides

an indirect relationship between soil water repellency and soil acidity. Seaton et al. [72] considered that the relationship between soil pH and water repellency was due to differences in the soil bacterial composition.

The accumulation of plant litter is important in forest soils because this supports microbial activity and the accumulation of soil hydrophobic substances. Therefore, the measured values of the original forests and those in the afforested vineyards indicate medium to extreme soil water repellency. In addition, Jex et al. [88] confirm that thick forest litter significantly increases water repellency. The combined thicker litter layer and dead herbaceous undergrowth create favorable moisture conditions for microscopic fungi, and their hyphae support water repellency in the soil surface. Seaton et al. [72], also acknowledge the effect of microbial composition on soil water repellency in their ecological theory. This states that soil water repellency is an ecosystem response to a stressful environment, as a means of protecting microbes and ensuring better resource allocation with plants.

Agricultural land management can also promote changes in soil water repellency. Alternative management to tillage and herbicides such as catch crops, straw mulches, chipped pruned branches, manure, and compost addition to the soils contributes to an increase in soil organic matter and then in the soil water repellency, although reducing the soil losses [89]. A study by González-Peñaloza et al. [90] showed how the time since organic farming management in citrus plantation is the key to understanding the changes in soil water repellency and soil infiltration characteristics.

Governmental agencies are promoting the enhancement of soil organic matter in order to achieve sustainable soil management due to the land degradation suffered by vineyards [91,92] as a consequence of high erosion rates, which have led to a non-sustainable situation [93]. Our research provides information about the risk of increasing soil water repellency and causing a reduction in the soil infiltration rates as a consequence of those practices.

4.3. Infiltration

The infiltration rate decreases over time in wettable soils (Figure 4), which can be related to the sorption of water into wettable capillary pores [94], whereas the infiltration rate increases in non-wettable soils, as reported by a number of authors [94–97]. Researchers attribute the gradual increase in infiltration rate to the water repellent properties of the soil [56,95,98,99]. Similar experiments to ours, and in similar conditions, were performed by Orfánus et al. [100]. Their Decagon mini-disk infiltrometer-aided experiment recorded a significant decrease in hydraulic conductivity at $h = -2$ cm in their water repellent sandy soils. The convex curves for water repellent soils are clearly apparent in the cumulative infiltration vs. time graphs (Figure 5), and concave curves are restricted to wettable soils [96].

Researchers have offered the following hypotheses for why the rate of infiltration increases in water repellent soils:

- the gradual decrease in soil water repellency with increasing depth [98];
- the dissolution of organic matter from soil in infiltrating water, which reduces water surface tension and therefore also reduces the contact angle [98];
- the dynamic change (decrease) of contact angles in bulk media [94];
- the dynamic change (increase) in the wettable fraction of the soil [101];
- the build-up of local pressures in the presence of internal ponding [56,95].

Additional research results can be found in Bughici and Wallach [102], who recently employed the sessile drop test to establish the kinetics of the contact angle decrease over time, and in Beatty and Smith [101], who noted that the rate of change in soil wettability and the rate of change in soil wettable fraction are primary drivers of water flow when the contact angle changes substantially over time. Although the kinetics of these changes is important in determining the course of infiltration in water repellent soils, it is apparent that all of the above effects can contribute to the increased infiltration rate over time.

Moreover, although infiltration theory indicates that the negative C_1 parameter values in the lower diagram in Figure 6 are physically impossible, similar negative values were reported by Beatty and Smith [101]. It is therefore most likely that the contact angle decreases with time, and that the decrease in water repellency during infiltration is responsible for the negative C_1 values.

Doerr et al. [99] consider that a significant reduction in the rate of water infiltration to the soil is one of the negative effects of soil water repellency, regardless of the mechanisms involved in the infiltration process. The reduced infiltration rate is most pronounced in the initial stages, and this causes a high susceptibility of water repellent soils to the formation of surface runoff (Hortonian flow). There is then less rainwater retention in catchments during heavy rains and significant intensification of erosion processes.

4.4. Implications

Grape production has long been considered an aggressive crop for soils because of the essential repetitive tillage that results in loss of vegetation cover and soil organic matter, and soil erosion. Thus, a millennia-old vineyard crop produces degraded soils. Rodrigo-Comino et al. [93] add that these negative effects confirm the current unsustainable vineyard management. Researchers are now investigating alternative management practices to reduce soil losses and soil degradation. These include the use of straw mulches [103], cover crops [104], manure [105], service crops [106], and organic farming [107]. These nature-based solutions should also enhance ecosystem services [108].

Our research established that vineyard abandonment transforms the soil into a body enriched in organic matter and plant cover, and this then induces a decrease in pH and a lower infiltration rate due to the impact of water repellency. Zhang et al. [109] consider that abandonment results in decreased infiltration rates on the millimeter (matrix) scale, and increased water repellency could force macropore flow into the deeper soil layers, where the extra water will help vegetation recovery. Alagna et al. [110] also reported low infiltration rates in Eastern Iberian Peninsula vineyards, whereas other researchers have demonstrated that forest soils are stable, with high infiltration rates [111].

5. Conclusions

This study in the wine-growing region of the Little Carpathians mountain range established significant differences between soils in cultivated vineyards, afforested vineyards, and forest areas.

The slightly acidic-to-alkaline vineyard soils with low organic carbon content changed to acidic soils with higher organic carbon content following afforestation. The differences in soil pH and organic carbon content are responsible for the significantly different hydrological properties in the vineyard and forest soils. In particular, the susceptibility to soil water repellency is greater in the forest and afforested soils. Although vineyard soils were wettable in all research sites, the forest and afforested soils were strongly to extremely water repellent, dependent on organic carbon content. The only exception to this is the transitional afforested soil, which is less water repellent than expected because of higher soil pH.

In conclusion, the difference in soil wettability or repellency has a major effect on infiltration processes. The infiltration rate under near-saturated conditions was significantly lower in the afforested soil than in the vineyard. However, water repellency causes a gradual increase in the infiltration rate over time, and this contrasts sharply with wettable soil in which the infiltration rate decreases with time. Water repellency also causes the physically impossible negative sorptivity values determined in afforested soil.

Finally, our research demonstrates that vineyard abandonment promotes changes in the soil system, which induce restoration of original soil properties under forest management, and this results in increased water repellency and reduced soil matrix infiltration rates.

Author Contributions: Conceptualization, P.D., A.C.; formal analysis, A.H., P.D., A.C., and J.K.; methodology, P.D., A.C., and J.K.; writing—review and editing, A.H., P.D., A.C., and J.K.; funding acquisition, P.D. and J.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Slovak Scientific Grant Agency VEGA projects 1/0712/20, 2/0118/18 and 2/0096/19.

Conflicts of Interest: The authors declare no conflict of interest.

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