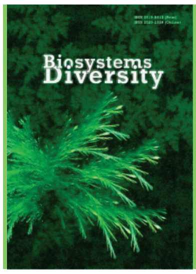


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# Age estimation of black locust (*Robinia pseudoacacia*) based on morphometric traits

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The use of black locust (*Robinia pseudoacacia* L.) is still controversial, especially in managed forests, due to its invasive nature. The black locust has been proven effective in reclamation of degraded lands when native species are not an alternative in the face of the climate change and desertification. Therefore, the importance of black locust in European ecosystems remains a matter of debate. Of course, it is an adventitious species originating from another continent. However, the ecological characteristics of the species in its natural range are very useful for ensuring the restoration of vegetation cover in areas that have experienced significant anthropogenic pressure. This species has a large number of important and useful features that make it an important agent in the forestry system and provide significant environmental and economic benefits. The status of black locust as an invasive species, i.e. one that is capable of uncontrolled spread, remains speculative. Such a conclusion requires various studies, including those identifying exact age of the plants based on morphometric parameters. In our study, we tested the hypothesis that plant height and trunk diameter will allow for an accurate assessment of black locust age. The plants of black locust were measured in the zone of spontaneous self-seeding of plants from a planted 60-years-old forest. The plants dispersed towards a fallow land, formed in the corner of an agricultural field. The spreading began 15 to 20 years ago. The plants are mainly propagated by seedlings. An expert estimated the age of the plants visually. The measured trees were cut to obtain cross sections to account for the number of annual rings. A total of 68 trees were examined for morphometric characters. Black locust communities during self-dispersal are represented by individuals of different ages. The spatial pattern of distribution of individuals of different ages can reveal the spatial and temporal dynamics of the formation of spontaneous populations of black locust. For this purpose, it is critical to accurately identify the age of a large sample. Expert estimation of age is fast and fairly accurate, but it depends greatly on the qualifications of the expert and oftentimes plant ages are underestimated, especially in the early stages of population development. Plant height is also a good predictor of plant age, but the model gives poor predictions for plants older than 10 years. The tree height ranged 2.3 to 16.0 meters. The diameter at breast height (DBH) ranged 1.0 to 17.5 cm. The diameter at the root collar (DRC) ranged 1.6 to 21.7 cm. The age of the studied trees, determined by the number of annual rings per transect, ranged 6 to 17 years. The age of the trees according to the expert estimates was 8.2 ± 4.8 years. The expert estimates of age and the age according to the number of annual rings were statistically significantly different. The expert estimates of tree age were linearly related to tree size, while estimates of the number of annual rings showed a logarithmic relationship with tree height. Expert estimates also showed a closer relationship with tree height, while the relationship of estimates based on the number of annual rings had a slightly lower dependence on the morphometric traits. Regression analysis showed that there is a linear relationship between morphometric traits of the black locust. The coefficient of determination for the dependence of diameter at breast height on tree height was 0.96, and for the dependence of diameter at the base of the trunk on diameter at breast height was 0.97. This indicates a high level of multicollinearity of these morphometric traits when considering them as predictors of plant age. Taking into account the diameter at breast height and the diameter at the level of the root collar significantly improved the predictive ability of the model for identifying the age of the black locust trees.

*Keywords*: reclamation; horticulture; bioenergetic; spatial ecology; regression; biometry.

## Introduction

European forests for a long time have been under the influence of human activity, undergoing various forms of exploitation. The form, organization and structure of forests are modified by anthropogenic impacts (Pötzelsberger et al., 2020). Large-scale introduction of alien species into European gardens, parks, and finally forests occurred after the discovery of America in the late 15th century. At least 145 adventive tree species are currently present in European forests, and almost half of them originate from North America (Brus et al., 2019). The natural range of the black locust (*Robinia pseudoacacia* L., Fabaceae) spans the eastern part of North America in the Appalachian Mountains to the Ozark Plateau. This species was introduced to Europe in 1601 (Nicolescu et al., 2020). An English naturalist, gardener, collector, and traveler John Tradescant the Elder sent seeds to his friend Jean Robin, who was the gardener (or arborist) to the French kings Henry III, Henry IV, and Louis XIII. Jean Robin planted black locust seeds in his garden (now Place de la Dauphine in Paris) (Nicolescu et al., 2020). This species was initially used as a park or garden tree, but in the mid-1700s and 1800s it began to be widely cultivated in European forests. Black locust was later widely used in windbreak forest belts, and also as a nitrogen-fixing species for land reclamation (Bijak & Lachowicz, 2021). The species was introduced to the gardens and parks of Ukraine in the late eighteenth century, and in the early nineteenth century it began to appear in forests. Black locust has become an economically valuable multifunctional species in many parts of Europe (Nicolescu et al., 2020). Black locust is broadly grown as an ornamental tree in urban parks. This species lives well in urban environments as it is tolerant to soil salinity and air pollution (Alilla et al., 2022). In addition to its decorative role in parks, gardens and alleys, black locust has also been used as a street tree and to mitigate urban pollution (Nicolescu et al., 2018). The high combustion potential of the wood, which is produced quickly and in sufficient quantities, has led to the extensive utilization of black locust as an energy crop. Black locusts consequently became the most widespread adventive species of broadleaf trees in Europe. Currently, it occupies the area of more than 2.3 million hectares. Therefore, black locust can be considered one of the most widespread, as well as economically and ecologically important non-native tree in Europe (Latchininsky, 2013).

The black locust has many positive socioeconomic effects. The influence of black locust on the soil properties plays an important role in the land use and management of ecosystems. Black locust improves soil properties and increase soil fertility. The tree has been successfully introduced as a nitrogen-fixing species, which helps supporting nitrogen pools in the soil, increases the return of nitrogen from the litter and increases the rate of nitrogen mineralization in soil (Rice et al., 2004). Nutrient content in the surface soil layer and soil moisture improved with age of black locust, but photosynthetically active radiation at the soil level and soil moisture in deeper soil layers decreased with age compared with the control conditions (Qiu et al., 2010). The planting with *R. pseudoacacia* of different ages had higher cover, fewer species in herbaceous plant communities, but higher β-diversity compared with the control conditions, and differed in the species composition. These structural and species composition variations were attributed to the effects of soil fertilization due to the nitrogen fixation by *R. pseudoacacia*, which promoted colonization by weeds and ruderal species, and also to the capture of light by the tree canopy, which excluded photophilous species, most of which were perennial herbaceous plants that were the dominant species in the control conditions (Kou et al., 2016). Black locust plantings prevent and control soil erosion. The positive effect on the erosion resistance of soils is due to the improvement of physical and chemical properties of soils in black locust plantations. Black locust has been proved to be effective in windbreaks. The driving force behind the widespread use of the species is its great potential to protect agricultural fields from wind (Ciuvăț et al., 2022). Litter cover in plantations and plant roots can effectively control erosion (Wang et al., 2017). This species can appreciably increase the cation exchange capacity of the soil, the content of organic carbon, total nitrogen, nitrates, the ratios of carbon to nitrogen and carbon to phosphorus, as well as the activity of some enzymes such as alkaline phosphatase and invertase, as compared with the natural ecosystems (Qiu et al., 2010). Experiments suggest that black locust plantations can double the organic matter and nitrogen content of the soil. Black locust has also shown a notable stimulating effect, especially in forests after fires (De Marco et al., 2023). Black locust is able to sequester carbon monoxide from the atmosphere.

Black locusts have long been used in the reclamation of disturbed lands. Reforestation with black locust is considered a successful method used to rehabilitate areas that had been disturbed by open-pit mining (Vlachodimos et al., 2013). Black locust is used in areas reclaimed after mining due to its fast development, with high biomass generation, high calorific efficiency of biomass and the ability to regenerate (Kanzler et al., 2015). Used for the purposes of rehabilitation of land altered by surface mining, this tree has been effective in restoring the soil cover and nutrient content in it (Yuan et al., 2018). Symbiosis of plants with atmospheric nitrogen-fixing bacteria significantly increased the efficiency of biological remediation of disturbed lands (Pietrzykowski et al., 2018). Nitrogen-fixing tree species promote physical and chemical modifications of anthropogenic soils. The accumulation of organic matter and dispersion of soil microorganisms and animals were observed as a result of the cultivation of such species (Józefowska et al., 2020). Black locust symbiotic N fixation increases the concentration of $NO_3$ in the soil. The source of increased $NO_3$ content in the soil is high N fluxes from mineralization and nitrification of leaves and root litter. Besides increasing the nitrogen content of the soil, symbiotic nitrogen fixation can also increase the content of organic matter in soil (Johnson & Curtis, 2001).

However, black locust should also be noted as one of the most invasive species in the world (Vítková et al., 2017). It is officially regarded as invasive in only 13 of the 35 European countries (Brus et al., 2016). In Germany, forest experts define black locust as a "partially invasive species" because its dispersal ability is limited to open fields, while the tree is not found in dense forests with a closed canopy. At the same time, the Slovenian foresters do consider black locust an invasive species (Rudolf & Brus, 2006). Black locust, as a photophilic pioneer species, can drastically and rapidly alter a specific habitat they invade, imposing a negative ecological impact on a native vegetation (Vítková et al., 2017). Black locust is reported to reduce biodiversity mainly by limiting access to light to the plants growing under the canopy, as well as by changing the microclimate or soil conditions (nitrification and acidification) (Lazzaro et al., 2018). However, there are strong evidences that this species becomes a habitat for numerous flora, arthropods, avian and mammalian species. The tree has naturalized and formed self-sustaining populations throughout the sub-Mediterranean and temperate regions under natural conditions that are not maintained or dependent on humans (Pyšek et al., 2009).

The use of black locust is still being discussed, especially in forest management, due to its invasive nature (Vítková et al., 2017). Nevertheless, it is reasonable to introduce this species to extremely unfavourable post-industrial areas where only a few species can grow. In addition, there is a need to consider not only native species of trees and shrubs, but also the climate change and increasingly common extreme weather events such as droughts. Prolonged droughts, which are increasingly common due to the global climate change, negatively affect native plants. Black locust is considered a solution to the problem of degraded lands when native species are not an alternative in the context of the climate change and desertification (Ciuvăț et al., 2022).

Thus, the importance of black locust in European ecosystems remains debatable. Of course, it is an adventive species originating from another continent. But the ecological features of the species in its native range are very useful for providing restoration of vegetation cover in areas that had experienced significant anthropogenic pressure. This species has a large number of important and beneficial features, which makes it influencial in the forestry system and can produce significant environmental and economic outcomes. The status of this species as an invasive species, i.e. one that is capable of uncontrolled spread, remains speculative. To make such a conclusion, various studies should be carried out, including those identifying the exact age of plants based on morphometric parameters. We wanted to test the hypothesis that plant height and trunk diameter can provide an accurate estimation of the age of black locust.

## Material and methods

Tree observations were made in the fall of 2022. The black locust plants were measured in the zone of spontaneous self-seeding from a 60-years-old planted forest (48°15'52" N, 35°09'51" E). The dispersal occurred in the direction of fallow land, which was formed in the corner of an agricultural field. The black locusts began to spread around 15 to 20 years ago. The plants mainly reproduced by means of seedlings. Diameter at breast height (DBH) and diameter at the root collar (DRC) were measured to the nearest 0.1 cm, and height (H) of all the trees was measured to the nearest 0.01 m. Diameter and height were measured using an optical height meter (PM-5/1520 model; Suunto Instrument Co., Helsinki, Finland). At the same time, an expert estimated the age of the plants visually. The measured trees were cut to obtain cross-sections to account for the number of annual rings (Fig. 1).

**Fig. 1.** Cross-section of a black locust trunk for age identification

Bartlett's test for heteroscedasticity was performed using the olsrr package. Descriptive statistics for expert estimates of tree age, which were censored variables (represented by a range of values with a minimum and maximum possible value), were calculated using the fitdistcens function from the fitdistrplus package. The regression parameters were estimated using the ProjectR.

**Results**

A total of 68 trees were studied for the morphometric traits. The height of the trees varied 2.3 to 16.0 meters (mean ± standard deviation was 8.9 ± 4.1 meters). The height distribution did not deviate statistically significantly from the normal law (the Kolmogorov-Smirnov test was d = 0.10, P = 0.48). The diameter at breast height (DBH) ranged from 1.0 to 17.5 cm (mean 8.2 ± 4.9 cm). The distribution of this parameter did not deviate statistically significantly from the normal law (the Kolmogorov-Smirnov test was d = 0.09, P = 0.64). The diameter at the root collar (DRC) ranged 1.6 to 21.7 cm (the mean measuring 10.9 ± 5.9 cm). The distribution of this indicator did not deviate statistically significantly from the normal law (the Kolmogorov-Smirnov test was d = 0.11, P = 0.40).

The age of the studied trees, as estimated according to the number of annual rings at the cross sections, varied 6 to 17 years (the mean of 11.6 ± 3.7 years). The distribution of this indicator did not deviate statistically significantly from the normal law (Kolmogorov-Smirnov test was d = 0.15, P = 0.09) (if age is considered as a continuous variable) or from the Poisson law (Kolmogorov-Smirnov test was d = 0.13, P = 0.39). The age of trees according to the expert estimates was 8.2 ± 4.8 years. The expert estimates of age and the age based on the number of annual rings were statistically significantly different (P < 0.001). The expert estimates of tree age were linearly dependent on the tree size, while the estimates based on the number of annual rings showed a logarithmic dependence on tree height (Fig. 2). The expert estimates also had a closer dependence on the tree height ($R^2$ = 0.96–0.99), while the estimates based on the number of rings had a slightly lower dependence on morphometric traits ($R^2$ = 0.83).

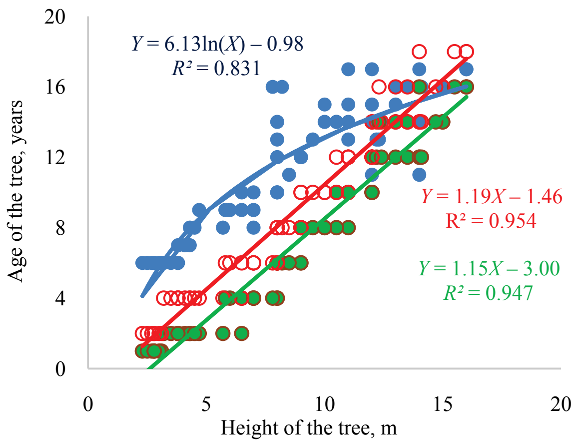


**Fig. 2.** Dependence of tree age on tree height: the blue colour is the age estimate based on the number of annual rings; the red colour is the expert estimate of the upper age limit; the green colour is the expert estimate of the lower age limit

The bootstrap modified robust Brown-Forsythe Levene-type test based on the absolute deviations from the median with modified structural zero removal method and correction factor revealed non-homogeneity of variance of diameter at breast height along the height of the tree and diameter at the base of the trunk (Test Statistic = 4.4, P = 0.006 and Test Statistic = 4.3, P < 0.001, respectively). The variation of these indicators increased with tree height.

The regression analysis revealed a linear relationship between the morphometric traits of black locust (Fig. 3). The coefficient of determination was 0.96 for the dependence of diameter at breast height on tree height, and 0.97 for the dependence of diameter at the base of the trunk on diameter at breast height. This indicates a high level of multicollinearity of these morphometric traits when considered as predictors of plant age. Therefore, we used tree height as a predictor of plant age, as well as the residuals of the regression of dependence of diameter at breast height on tree height, which was calculated by the formula:

$$I_1 = DBH + 2.32 - 1.18\,H,$$

where $I_1$ was the residual of the regression model, DBH was the diameter at the base of the trunk (cm), and H was the height of the tree (m).

The regression model fully explained the whole linear component of the dependence of diameter at breast height on tree height, so the linear Pearson correlation coefficient I1 and H was not statistically significant (r = 0.0073, P = 0.95).

Also, residuals of the regression relationship between diameter at trunk base and diameter at breast height, calculated using the formula, were used as a predictor of tree age:

$$I_2 = DRC - 0.32 - 0.42\,H - 0.85DBH,$$

where $I_2$ was the residual of the regression model, DRC was the diameter at the base of the trunk (cm), H was the tree height, and DBH was the diameter at the base of the trunk (cm). The predictor $I_2$ did not have a statistically significant relationship with either H (r < 0.001, P > 0.95) or $I_1$ (r < 0.001, P > 0.95).

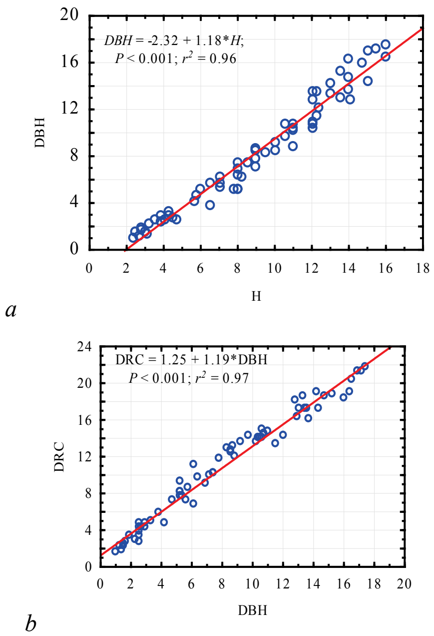


**Fig. 3.** Dependence of diameter at breast height (DBH, cm) on tree height (H, m) (*a*) and dependence of diameter at root collar (DRC, cm) on diameter at breast height (DBH, cm) (*b*)

The fact that tree height and trunk diameter naturally increased with age was trivial (Fig. 4). The data showed that with increasing tree age, variation of the morphometric traits increased, indicating heteroscedasticity. Bartlett's test indicated that the hypothesis about the equality of variance of tree height, DBH, DRC, $I_1$, and $I_2$ between all age classes could be rejected with a probability of P < 0.001. The increase in morphometric traits was even up to the age of about 10 years, and after this age the variation of traits increased significantly.

For the Poisson GLMs that were fitted, tests for overdispersion and model fitting were required. The Poisson GLMs assume that the mean and variance of the response variable increase at the same rate. This assumption needs to be confirmed. A residual deviation of the fitted model that is greater than the residual degrees of freedom indicates presence of overdispersion. An overdispersion means that the Poisson distribution does not adequately model the variance and is not suitable for analysis. The values exceeding 1.2 are problematic. For the estimated models, the overdispersion was 0.37–0.73, indicating that the models fit the assumption underlying the analysis. As the complexity of the models increased, the explained variance increased (from 0.71 to 0.86). The AIC criterion indicated that the model with three predictors (Regression 3) was the best. The model misfit in the Poisson GLM was assessed by plotting the Pearson residuals against the fitted values and against each covariate in the model (Fig. 5). This approach also indicated that the model with three predictors (Regression 3) was the best. The residuals of Regression 2 and 3 showed a clearly identifiable nonlinear component of age variation that was not explained by these models.

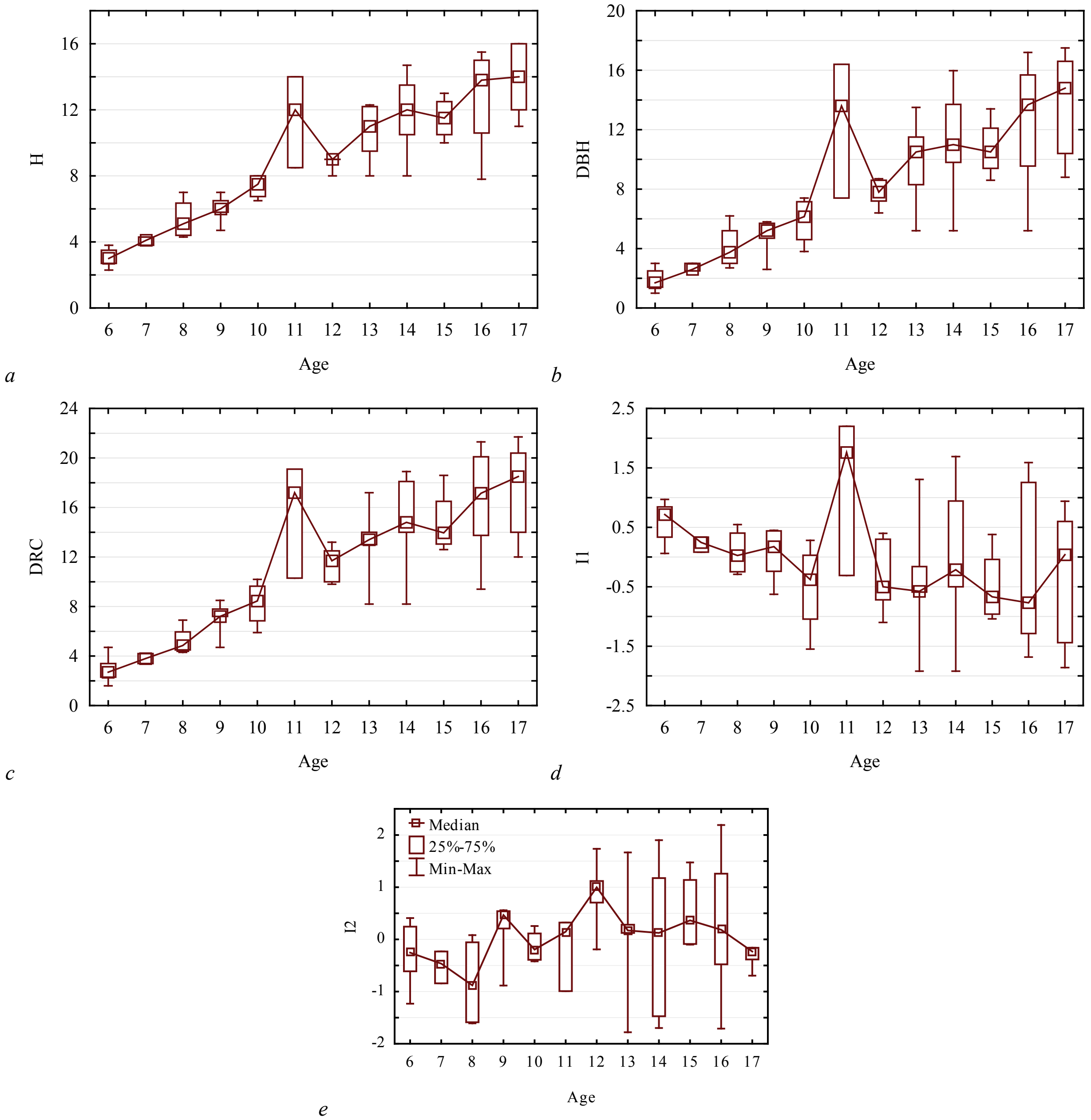


**Fig. 4.** Dependence of morphometric traits on tree age (N = 68): the abscissa axis is the age of the trees, years; the ordinate axis is the height of the tree, meters (*a*), diameter at breast height, cm (*b*), diameter at the root collar, cm (*c*), $I_1$ and $I_2$ are the residuals of the regression models (*d*, *e*)

Thus, the formula for calculating the age of black locust (*R. pseudoacacia*) trees from 5 to 18 years by morphometric traits is as follows:

$$Age = e^{1.7+0.08\cdot H-0.12\cdot(DBH+2.32-1.18\cdot H)+0.1\cdot(DRC-0.32-0.42\cdot H-0.85\cdot DBH)},$$

where from:

$$Age = e^{1.7+0.018\cdot H-0.2\cdot DBH+0.097\cdot DRC},$$

where Age is the age of the tree (years), H is the height of the tree (m), DBH is the tree trunk diameter at breast height (cm), DRC is the diameter at the root collar (cm).

## Discussion

Black locust is considered an invasive species that is capable of uncontrolled spread. Our point of view is the opposite: this species is very useful for sustainable ecological balance in areas that have been heavily impacted by human activity, and the ability of black locust to spread is one of its positive features. The tree spreads only in ecosystems disturbed by humans, whereas in a competitive environment, it is quickly outcompeted by other species and loses the competition. To address this issue, detailed studies of *Robinia* populations are needed. Cases of spontaneous spread of black locust to adjacent territories, which is technically an invasion, are of particular concern. Black locust is a photophilous pioneer species that is able to quickly disperse and colonize a wide range of xeric-mesophytic habitats, including steep cliffs or toxic man-made substrates (Cierjacks et al., 2013).

Black locust is particularly tolerant to significant disturbance followed by neglect and spontaneous succession over several years or decades, which is common in present-day landscapes. This species is an important dominant component of tree communities in numerous habitats in warm parts of Europe. Usually, populations in a landscape are interconnected, and black locust is able to disperse efficiently on a local scale and persist in place during the first decades of secondary succession. It dominates during the early stages of forest regeneration (Radtke et al., 2013) and successfully colonizes open spaces in suburban wastelands, mining areas, abandoned fields and pastures, gaps in forest or areas damaged by fire (Maringer et al., 2012). Black locust is a relatively weak competitor, growing in mixed stands of fast-growing early successional species, both native and alien: trees such as *Betula pendula*, *Populus tremula*, *Pinus sylvestris*, *Acer negundo*, and *Ailanthus altissima*, and shrubs, such as *Prunus spinosa* or *Lycium barbarum*. Seedlings of slow-growing native trees, such as oak, lose in competition with black locust (Vítková et al., 2017).

**Table 1**
Regression dependences of tree age on morphometric parameters estimated by the Poisson GLM method (a log link function, null deviance = 176.4)

| Regression | Predictor* | Estimate ± standard error | *z*-statistic | *P*-level | Residual deviance | Pseudo-$R^2$ | AIC | Overdispersion |
|---|---|---|---|---|---|---|---|---|
| 1 | Intercept | 1.770 ± 0.098 | 4.44 | <0.001 | 48.2 | 0.71 | 290.9 | 0.73 |
| | H | 0.072 ± 0.009 | 10.38 | <0.001 | | | | |
| 2 | Intercept | 1.730 ± 0.100 | 3.39 | <0.001 | 34.3 | 0.79 | 278.9 | 0.53 |
| | H | 0.075 ± 0.009 | 10.82 | <0.001 | | | | |
| | $I_1$ | –0.112 ± 0.037 | –3.71 | <0.001 | | | | |
| 3 | Intercept | 1.700 ± 0.103 | 2.75 | 0.006 | 23.9 | 0.86 | 270.5 | 0.37 |
| | H | 0.078 ± 0.010 | 10.81 | <0.001 | | | | |
| | $I_1$ | –0.117 ± 0.037 | –3.59 | <0.001 | | | | |
| | $I_2$ | 0.097 ± 0.038 | 3.26 | 0.002 | | | | |

*Note*: * H is the height of the tree (m); $I_1$ and $I_2$ are the residuals of the linear models.

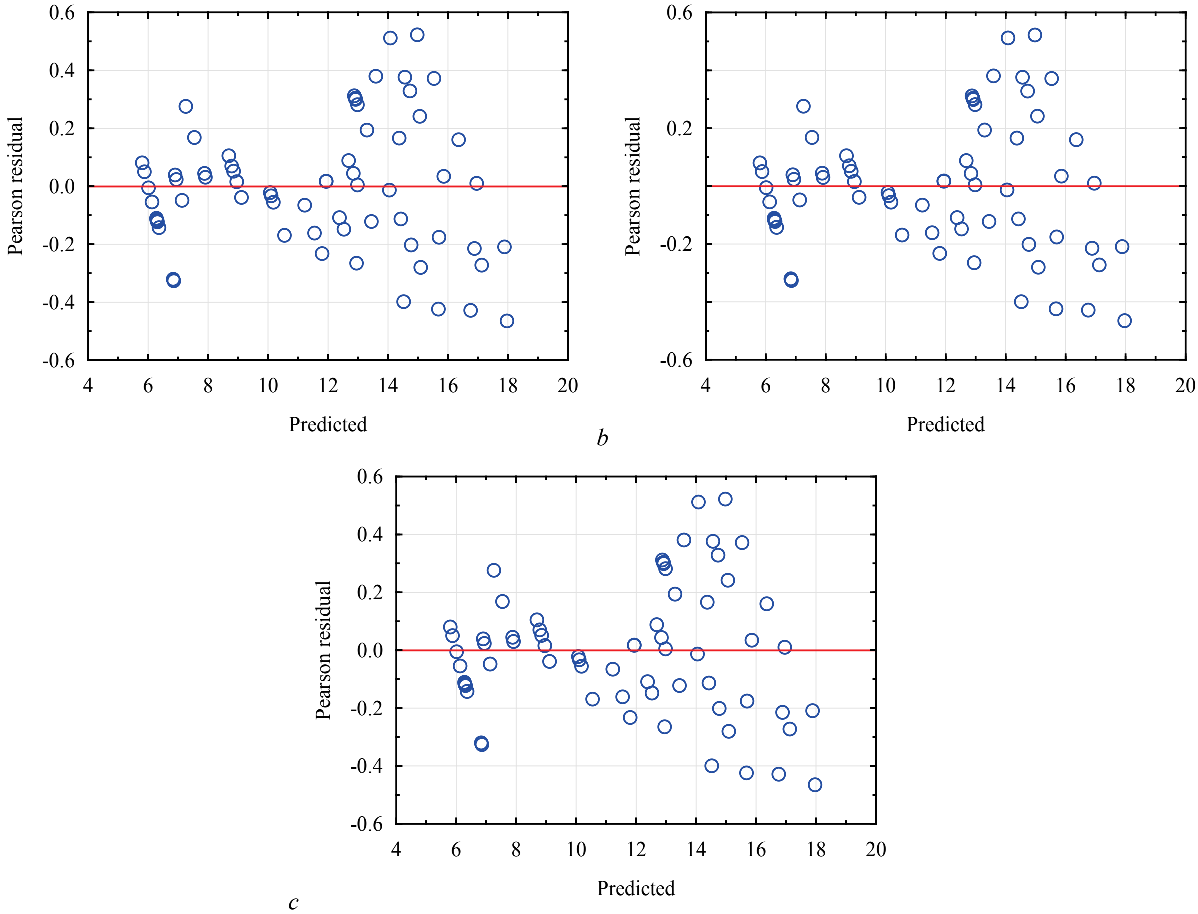


**Fig. 5.** GLM model fit test (N = 68): *a* is the test for Regression 1, *b* is the test for Regression 2, *c* is the test for Regression 3; the abscissa is the predicted value of tree age based on the respective model, the ordinates are the Pearson residuals of the regression models

Black locust propagates over small distances, except for shady, humid or permanently disturbed areas, locally up to 1 m per year due to horizontal elongation of roots and ramets that form a connected root system (Cierjacks et al., 2013). Black locust is extraordinarily resistant to unfavourable environments compared to other tree species. Under extreme lighting circumstances, it creates a stable bud bank, including buds on roots, stems and branches, which allows it to respond quickly to the opening of the canopy after disturbance. The tree forms numerous root offspring, even in trees over 70 years old. Compared to seedlings of other species of the same age, they are taller, grow faster (up to 4 m annually) and reach reproductive maturity earlier (Vítková & Kolbek, 2010). Mechanical destruction of roots or trunks, used as a regeneration method in forestry, leads to an increase in trunk density and rejuvenation of black locust stands, which in turn leads to the proliferation of compact clonal colonies that cover areas of several hundred square meters (Krízsik & Körmöczi, 2000).

Although black locust can spread rapidly over short distances, new populations are not easily developed. Long-distance dispersal is largely dependent on anthropogenic vectors, such as purposeful planting and transportation of soil with seeds and roots (Pyšek et al., 2012) or by motorized transport (von der Lippe & Kowarik, 2008). Black locust seeds are dispersed mainly by gravity. The natural spread of the seeds is constrained by its rather heavy grain, which is mainly dispersed by gravity and wind near a source tree. Long-distance dispersal by the natural process is not very common, although there are examples, including dispersal by water, wind, and animals. The greatest potential for long-distance spread occurs when black locust grows in riparian areas. The seeds float in water, and although their relatively heavy weight means they do not travel as far through the water as seeds of some other species, access to flowing water is estimated to increase the average dispersal distance of black locust seeds by 80 times (Säumel & Kowarik, 2013). Experimental results show that about 20% of the pods transported by rivers travel a distance of more than 1,200 meters (Säumel & Kowarik, 2013). On the snow surface, a seed was found to be able to travel up to 67 meters from a parent plant (Morimoto et al., 2010). The seeds are toxic to many livestock and wildlife species, so long-distance dispersal by animals is rare. Nevertheless, black locust seeds have been confirmed to be carried by pigs and birds(Cierjacks et al., 2013).

An individual black locust tree produces up to 12,000 seeds/m$^2$ in mono-dominant stands (Marjai, 1995). The germination rate of black locust seeds is typically low due to the thick seed coat, but once in the soil, they can remain viable for decades. The intensity of germination of seeds in the field depends on environmental conditions in which they maturate (Baskin et al., 2000). The percentage of seed germination in natural conditions is low, ranging 3.5% to 16.3% (Roberts & Carpenter, 1983). Seedlings are sensitive to shading, their mortality being high in closed herbaceous vegetation and forests, while they survived in disturbed areas with lighter and more open soil, especially on burned areas (Maringer et al., 2012). The relatively slow spread through seeds, low germination rate and poor long-term ability to compete with trees such as *Tilia*, *Acer* or *Ulmus*, which form closed-canopy forests, are the main factors limiting the establishment of new populations of black locust. In this respect, black locust differs from other successful invaders that colonize disturbed areas even at great distances from an original plant due to their high germination rate and high ability to spread by water, wind or birds. Black locust spreads locally by its root system, forming dense clonal colonies once it has settled in a certain area. Black locust grows mainly in clear-cuts, abandoned pastures, or disturbed roadsides. The species has historically been an important colonizer of burned areas. Although it typically propagates by seed germination, the most common method of regeneration is sprouting from stumps and roots. A characteristic of black locust is that early sprouts grow rapidly, reaching up to 8 m height in 3 years. The growth rate usually decreases in 10 or 20 years old and older stands, except stands on sites with high nutrient content. High trunk mortality may be observed in mature stands due to pest attacks. The high mortality of black locust over time is a mechanism of early succession, which provides conditions for the development of codominant species by creating a gap in the black locust canopy (Boring & Swank, 1984).

Assessing age of trees is very important to study the dynamics of spontaneous growth of black locust. In plantations, this problem is to some extent solved because time of planting and age of seedlings used are usually known. For mature stands with an unknown history, age of the trees can be determined by obtaining a core sample and recalculating annual rings. For young trees, this approach is not very convenient, because obtaining a core sample may result in the destruction of a young plant. In addition, coring may still provide a limited number of measurements due to the labour intensity of the procedure. Expert estimation visually is a convenient alternative that can provide large amounts of data with moderate resource use. Our findings indicate that the visual estimations produce good results, but the age was systematically underestimated. Obviously, an expert gains experience in accounting for tree parameters in certain conditions, and therefore it is important for him or her to adjust their estimates to other environmental conditions. This is either impossible or requires unique professional experience. In addition, the expert subconsciously simplifies the tree growth pattern by representing the dependence of size on age as a linear function. Black locust is known to grow rapidly in height during the first 10–15 years both in its natural habitat and in Europe (Nicolescu et al., 2020). It should be noted that the subjective accuracy of the linear dependence is quite high for both the upper and lower limits of the estimated range. However, the actual pattern is a saturated curve, where the plant growth rate decreases over time. As a result, the expert estimates and the results obtained by counting annual rings are almost identical for trees aged 12–20 years, but for younger age categories, the expert estimates provide significantly underestimated values of tree age.

Our results are somewhat inconsistent with the findings that under the best conditions trees can reach 10 m height at the age of 5 years and 14 m at the age of 10 years (Rédei & Veperdi, 2009). Ten-meters height was observed for the trees older than 11 years, and the height of 14 meters was observed for the trees older than 16 years. The extreme environmental conditions for black locust growth in the steppe zone of Ukraine may be the most likely explanation for this delay in the plant growth rate. The literature data also indicate that rates of height growth were the highest during the first decade in the best sites with warm climates, rich and deep soils. The better the potential of the site, the earlier the maximum height growth occurs. The plant growth slows down after 15 years, although growth remains relatively fast in older trees. Black locust stands in Europe can reach an average or dominant height of more than 20 m at 20 years of age and up to 25–30 m at 30 years of age (Nicolescu et al., 2020). Our results indicate almost monotonous increase in plant height up to the age of 17 years, although the absolute height values were lower than those observed under more favourable conditions. The reason for this lag may be less suitable conditions for plant growth, or because we have only studied the case of independent plant dispersal rather than a planting. It can be assumed that a population requires more resources, which also slows down plant growth. Shoots from seedlings are known to grow in height faster than root sprouts or plants that have grown from seeds up to 15–20 years of age. Later, this trend reversed, and the height of trees that grew from seeds became greater than of tree stands of the same age. Black locust trees have rapid early diameter growth, which can reach 3–4 cm in the first year under the best conditions. However, it is unclear how this pattern works under conditions of spontaneous plant dispersal and whether the inhibition of plant growth increases as individuals spread to new locations.

The height of a tree is a good predictor of its age. Fairly accurate estimates of age based on plant height can be obtained for young individuals up to 8–10 years old. For older trees, there were significant deviations between the predicted and experimentally determined ages from the regression model. The stand closure can be suggested to occur when plants reach the age of 10 years or more, after which there is a struggle for light due to the fact that the intra-population growth rate of individuals varies greatly. We hypothesized that additional morphological traits could significantly improve the model's predictive properties. A significant limitation for the use of additional morphological traits to create a regression model is the significant dependence of morphological traits on plant size, which results in multicollinearity between them. To prevent multicollinearity, we used the residuals of the regression models that identify the dependence of diameter at breast height on tree height (index $I_1$) and diameter at root collar on diameter at breast height (index $I_2$) as morphological indicators.

Index $I_1$ decreased with increasing plant age. In addition, the dependence of index $I_1$ on tree height can be described by a second-degree polynomial with a minimum observed at the height of ≈ 9 meters. This indicates that rapid growth at this age to achieve a competitive advantage occurs at the expense of accelerating the increase in plant height and delaying the rate of increase in plant trunk diameter. It is for the age group of 9 years and older that the predictive ability of the regression model deteriorates. Therefore, taking into account index $I_1$ significantly improves the properties of the regression model. The maximum diameter growth in such areas occurs at the early age: up to 10 years. The better the site potential, the earlier the maximum diameter growth occurs. As in the case with height, the shoots from logs had a larger diameter than those from the root offspring and those grown from seeds up to the age of 15–20 years. Later, the trend of diameter growth reverses: the diameter of stands that had grown from seeds exceeded the diameter of trees grown from tree stands of the same age. Index $I_2$ demonstrates a nonlinear dependence on the diameter at breast height with a minimum of the function also observed for the height of ≈ 9 meters. This indicates that the shape of the trunk at this age is most closely related to the shape of a cylinder, while at other ages (both younger and older) the shape of the trunk is more closely related to the cone shape with the base close to the root collar. Thus, the uneven rate of change of morphometric parameters during growth is the reason for their informational value for a more accurate estimation of plant age.

## Conclusion

Estimation of the age of black locust trees at the first stages of spontaneous dispersal is important for understanding the invasive potential of this species. Black locust communities during self-dispersal are represented by individuals of different ages. The spatial pattern of distribution of individuals of different ages can reveal the spatial and temporal dynamics of the formation of spontaneous black locust populations. For this purpose, accurate age estimation for a large sample size is critical. Expert age estimation is fast and fairly accurate, but this method is certainly closely associated with skills of an expert and provides systematically underestimated plant ages, especially in the early stages of a population development. Plant height is also a good predictor of plant age, but the model provides poor estimations for plants older than 10 years. Taking into account the diameter at breast height and diameter at the root collar significantly improved the predictive ability of the model for estimating the age of black locust.

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## References

Alilla, R., De Natale, F., Epifani, C., Parisse, B., & Cola, G. (2022). The flowering of black locust (*Robinia pseudoacacia* L.) in Italy: A phenology modeling approach. Agronomy, 12(7), 1623.

Baskin, J. M., Baskin, C. C., & Li, X. (2000). Taxonomy, anatomy and evolution of physical dormancy in seeds. Plant Species Biology, 15(2), 139–152.

Bijak, S., & Lachowicz, H. (2021). Impact of tree age and size on selected properties of black locust (*Robinia pseudoacacia* L.) wood. Forests, 12(5), 634.

Boring, L. R., & Swank, W. T. (1984). The role of black locust (*Robinia pseudoacacia*) in forest succession. The Journal of Ecology, 72(3), 749.

Brus, R., Pötzelsberger, E., Lapin, K., Brundu, G., Orazio, C., Straigyte, L., & Hasenauer, H. (2019). Extent, distribution and origin of non-native forest tree species in Europe. Scandinavian Journal of Forest Research, 34(7), 533–544.

Cierjacks, A., Kowarik, I., Joshi, J., Hempel, S., Ristow, M., von der Lippe, M., & Weber, E. (2013). Biological flora of the British Isles: *Robinia pseudoacacia*. Journal of Ecology, 101(6), 1623–1640.

Ciuvăț, A. L., Abrudan, I. V., Ciuvăț, C. G., Marcu, C., Lorenț, A., Dincă, L., & Szilard, B. (2022). Black locust (*Robinia pseudoacacia* L.) in Romanian forestry. Diversity, 14(10), 780.

De Marco, A., Napoletano, P., Panico, S. C., Memoli, V., Santorufo, L., Ruggiero, A. G., Colombo, C., Barile, R., & Maisto, G. (2023). Combined effect of black locust invasion and fire on soils of Mediterranean shrublands and pine forests. Catena, 220, 106656.

Johnson, D. W., & Curtis, P. S. (2001). Effects of forest management on soil C and N storage: Meta analysis. Forest Ecology and Management, 140(2–3), 227–238.

Józefowska, A., Woś, B., Pietrzykowski, M., & Schlaghamerský, J. (2020). Colonisation by enchytraeids as a suitable indicator of successful biological reclamation of post-mining technosols using alders. Applied Soil Ecology, 145, 103300.

Kanzler, M., Böhm, C., & Freese, D. (2015). Impact of P fertilisation on the growth performance of black locust (*Robinia pseudoacacia* L.) in a lignite post-mining area in Germany. Annals of Forest Research, 58(1), 1.

Kou, M., Garcia-Fayos, P., Hu, S., & Jiao, J. (2016). The effect of *Robinia pseudoacacia* afforestation on soil and vegetation properties in the Loess Plateau (China): A chronosequence approach. Forest Ecology and Management, 375, 146–158.

Krízsik, V., & Körmöczi, L. (2000). Spatial spreading of *Robinia pseudoacacia* and *Populus alba* clones in sandy habitats. Tiscia, 32, 3–8.

Kunakh, O. M., Ivanko, I. A., Holoborodko, K. K., Lisovets, O. I., Volkova, A. M., & Zhukov, O. V. (2022). Urban park layers: Spatial variation in plant community structure. Biosystems Diversity, 30(3), 274–288.

Latchininsky, A. V. (2013). Locusts and remote sensing: A review. Journal of Applied Remote Sensing, 7(1), 075099.

Lazzaro, L., Mazza, G., D'Errico, G., Fabiani, A., Giuliani, C., Inghilesi, A. F., Lagomarsino, A., Landi, S., Lastrucci, L., Pastorelli, R., Roversi, P. F., Torrini, G., Tricarico, E., & Foggi, B. (2018). How ecosystems change following invasion by *Robinia pseudoacacia*: Insights from soil chemical properties and soil microbial, nematode, microarthropod and plant communities. Science of the Total Environment, 622–623, 1509–1518.

Maringer, J., Wohlgemuth, T., Neff, C., Pezzatti, G. B., & Conedera, M. (2012). Post-fire spread of alien plant species in a mixed broad-leaved forest of the Insubric region. Flora – Morphology, Distribution, Functional Ecology of Plants, 207(1), 19–29.

Morimoto, J., Kominami, R., & Koike, T. (2010). Distribution and characteristics of the soil seed bank of the black locust (*Robinia pseudoacacia*) in a headwater basin in Northern Japan. Landscape and Ecological Engineering, 6(2), 193–199.

Nicolescu, V.-N., Hernea, C., Bakti, B., Keserű, Z., Antal, B., & Rédei, K. (2018). black locust (*Robinia pseudoacacia* L.) as a multi-purpose tree species in Hungary and Romania: A review. Journal of Forestry Research, 29(6), 1449–1463.

Nicolescu, V.-N., Rédei, K., Mason, W. L., Vor, T., Pöetzelsberger, E., Bastien, J.-C., Brus, R., Benčať, T., Đodan, M., Cvjetkovic, B., Andrašev, S., La Porta, N., Lavnyy, V., Mandžukovski, D., Petkova, K., Roženbergar, D., Wąsik, R., Mohren, G. M. J., Monteverdi, M. C., & Pástor, M. (2020). Ecology, growth and management of black locust (*Robinia pseudoacacia* L.), a non-native species integrated into European forests. Journal of Forestry Research, 31(4), 1081–1101.

Pietrzykowski, M., Woś, B., Pająk, M., Wanic, T., Krzaklewski, W., & Chodak, M. (2018). Reclamation of a lignite combustion waste disposal site with alders (*Alnus* sp.): Assessment of tree growth and nutrient status within 10 years of the experiment. Environmental Science and Pollution Research, 25(17), 17091–17099.

Pötzelsberger, E., Spiecker, H., Neophytou, C., Mohren, F., Gazda, A., & Hasenauer, H. (2020). Growing non-native trees in European forests brings benefits and opportunities but also has its risks and limits. Current Forestry Reports, 6(4), 339–353.

Pyšek, P., Chytrý, M., Pergl, J., Sádlo, J., & Wild, J. (2012). Plant invasions in the Czech Republic: Current state, introduction dynamics, invasive species and invaded habitats. Preslia, 84, 575–629.

Pyšek, P., Lambdon, P. W., Arianoutsou, M., Kühn, I., Pino, J., & Winter, M. (2009). Alien vascular plants of Europe. In: Nentwig, W. (Ed.). Handbook of alien species in Europe. Springer Netherlands. Pp. 43–61.

Qiu, L., Zhang, X., Cheng, J., & Yin, X. (2010). Effects of black locust (*Robinia pseudoacacia*) on soil properties in the loessial gully region of the Loess Plateau, China. Plant and Soil, 332(1–2), 207–217.

Radtke, A., Ambraß, S., Zerbe, S., Tonon, G., Fontana, V., & Ammer, C. (2013). Traditional coppice forest management drives the invasion of *Ailanthus altissima* and *Robinia pseudoacacia* into deciduous forests. Forest Ecology and Management, 291, 308–317.

Rédei, K., & Veperdi, I. (2009). The role of black locust (*Robinia pseudoacacia* L.) in establishment of short-rotation energy plantations in Hungary. International Journal of Horticultural Science, 15(3), 832.

Rice, S. K., Westerman, B., & Federici, R. (2004). Impacts of the exotic, nitrogen-fixing black locust (*Robinia pseudoacacia*) on nitrogen-cycling in a pine-oak ecosystem. Plant Ecology, 174(1), 97–107.

Roberts, D. R., & Carpenter, S. B. (1983). The influence of seed scarification and site preparation on establishment of black locust on surface-mined sites. Tree Planters' Notes, 34, 28–30.

Säumel, I., & Kowarik, I. (2013). Propagule morphology and river characteristics shape secondary water dispersal in tree species. Plant Ecology, 214(10), 1257–1272.

Vítková, M., & Kolbek, J. (2010). Vegetation classification and synecology of Bohemian *Robinia pseudacacia* stands in a Central European context. Phytocoenologia, 40(2–3), 205–241.

Vítková, M., Müllerová, J., Sádlo, J., Pergl, J., & Pyšek, P. (2017). Black locust (*Robinia pseudoacacia*) beloved and despised: A story of an invasive tree in Central Europe. Forest Ecology and Management, 384, 287–302.

Vlachodimos, K., Papatheodorou, E. M., Diamantopoulos, J., & Monokrousos, N. (2013). Assessment of *Robinia pseudoacacia* cultivations as a restoration strategy for reclaimed mine spoil heaps. Environmental Monitoring and Assessment, 185(8), 6921–6932.

von der Lippe, M., & Kowarik, I. (2008). Do cities export biodiversity? Traffic as dispersal vector across urban-rural gradients. Diversity and Distributions, 14(1), 18–25.

Wang, D., Yu, X., Zhang, J., Jia, G., Zhang, H., Liu, Z., & Hou, G. (2017). The impacts of *Robinia pseudoacacia* litter cover and roots on soil erosion in the Loess Plateau, China. Chemistry and Ecology, 33(6), 528–542.

Yuan, Y., Zhao, Z., Niu, S., Li, X., Wang, Y., & Bai, Z. (2018). Reclamation promotes the succession of the soil and vegetation in opencast coal mine: A case study from *Robinia pseudoacacia* reclaimed forests, Pingshuo mine, China. Catena, 165, 72–79.