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Comparing the effectiveness of random forest and generalized linear models in predicting ungulate browsing impact on Kyiv Polissya's young pine forests

Natalia Vysotska[1,2] ✉, *Oleksandr Khromuliak*[3], *Oleksandr Borysenko*[4,5], *Maksym Rumiantsev*[2], *Iryna Yashchuk*[6], *Oleksandr Kipran*[2]

[1] Estonian University of Life Sciences, Institute of Forestry and Engineering, Fr. R. Kreutzwaldi 5, Tartu, Estonia, e-mail: natalia.vysotska@emu.ee

[2] Ukrainian Research Institute of Forestry and Forest Melioration, Hryhoriia Skovorody 86, Kharkiv, Ukraine

[3] Dniprovsko-Teterivske State Forest and Hunting Enterprise, Kyiv, Ukraine

[4] University of Tartu, Department of Remote Sensing, Tartu Observatory, Toravere, Estonia

[5] National Aerospace University 'Kharkiv Aviation Institute', Department of Geoinformation Technologies and Space Monitoring of the Earth, Vadim Manko 17, Kharkiv, Ukraine

[6] State Enterprise 'Klavdiivska Forest Research Station', Kyiv, Ukraine

Abstract

Effective management of forest ecosystems requires accurate predictions of damage by ungulates, a challenge particularly acute in the Kyiv Polissya. This study aims to identify key drivers of ungulate browsing intensity and compare the effectiveness of the random forest model (RFM) and generalized linear model (GLM) in forecasting damage to young forests. We analysed field data from three experimental enterprises in the Kyiv region, covering a combined area of 71.4 thousand hectares and involving 275 experimental plots. The study identified ungulate population density as the most influential factor affecting browsing intensity, surpassing variables such as tree age, tree species ratio and forest type. In comparing models, RFM demonstrated superior predictive accuracy over GLM, highlighting its effectiveness in forecasting damage to young forests. The study highlights how machine learning enhances the accuracy of ecological predictions and underscores the significance of selecting variables thoughtfully during model development. The findings point to the need for flexible forest management strategies focused on regulating wild ungulate populations and protecting young forests.

Key words

browsing, tree species composition, ungulate density, tree damage, machine learning

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Introduction

The Scots pine (*Pinus sylvestris* L.) is the most widespread tree species in the forests of Ukraine, accounting for 35% (nearly 3.4 million hectares) of the country's total forest area (Spathelf et al. 2024). Despite the recognized impact of ungulates on forest structure, composition and succession (Shadura et al. 2004; Ramirez et al. 2019), detailed analyses of browsing patterns, especially in Polissya's unique ecosystem, are sparse. Our research focuses on roe deer (*Capreolus capreolus* L.), moose (*Alces alces* L.) and red deer (*Cervus elaphus* L.), which are known to cause considerable damage to young trees, thereby affecting the forests' economic value and ecological balance.

Previous studies have outlined factors such as animal density (Månsson et al. 2007), tree age (Kupferschmid 2018), structural and compositional aspects of the forest (Long et al. 2007) and forest management practices influencing browsing damage (Bergqvist et al. 2001; Vehviläinen and Koricheva 2006; Yevtushevskyi 2008; Bergvall and Leimar 2017), yet the complexity of interactions at different temporal and spatial scales demands further investigation (Pfeffer et al. 2021).

Ungulate browsing in young pine forests may not cause significant damage if it only involves browsing lateral shoots. However, damage to the central shoot of trees, stripping bark from the stem of plants or trampling leads to substantial economic losses due to decreased timber quality, growth rate and an increased proportion of dead trees (Lindmark et al. 2020). Investigating the influence of wild ungulates on the composition of tree species, tree regeneration and forest resilience is crucial for determining suitable forest recovery strategies, especially with increasing ungulate numbers (Perea and Gil 2014; Champagne et al. 2021). As ungulate populations grow, understanding their habitat preferences becomes essential for predicting browsing impact and implementing effective forest management strategies.

The accuracy of predictions regarding the probability of tree damage by ungulates is crucial for maintaining ecological sustainability and managing commercial forestry effectively. The random forest model (RFM) has demonstrated high predictive accuracy within data analytics and other fields, achieving notable precision in environmental research (Illanas et al. 2022). Similarly, the generalized linear model (GLM) can effectively estimate the effects of environmental factors on ungulate behaviour and the consequent risk of damage to forest areas (Hurley et al. 2017; D'Aprile et al. 2020; Traill et al. 2021). By comparing these models, we aim to identify the key drivers of ungulate browsing intensity and assess the effectiveness of each model in forecasting damage to young forests, thereby contributing to the development of adaptive forest management strategies focused on mitigating ungulate browsing impacts.

This study analysed datasets from the Kyiv region forests, focusing on variables such as ungulate density, animal browsing levels, tree species compositions and forest types. The objectives were to (i) identify the key drivers affecting ungulate browsing intensity in different forestry enterprises and (ii) compare the effectiveness of two forecasting models RFM and GLM in precisely predicting damage to young forests.

Material and methods

Study area

The study area is located in the north of Ukraine in Central Polissya within 50°36'and 51°06' north latitude and 29°18' and 30°42' east longitude in Kyiv region (Fig. 1).

In the study region, the climate is moderately continental with average temperatures annually ranging from 7 to 7.5°C. The period with an average daily air temperature above 0°C lasts 250 days, above 5°C for 205 days and above 10°C for up to 160 days. The average annual precipitation reaches 600–700 mm. The duration of snow cover lasts 70–95 days, with an average height of 20 cm (Ecological Passport of Kyiv region 2021). Overall, the climate of the research region is favourable for the successful growth of species, such as Scots pine (*Pinus sylvestris* L.), English oak (*Quercus robur* L.), European ash (*Fraxinus excelsior* L.), small-leaved lime (*Tilia cordata* Mill.), silver birch (*Betula pendula* Roth.), aspen (*Populus tremula* L.), black alder (*Alnus glutinosa* (L.) Gaerth.), European hazel (*Corylus avellana* L.), among others (Ostapenko and Tkach 2002).

The areas covered by forests are 26,746 ha in Vyschedubechanske Forestry Enterprise (Vyschedubechanske FE), 32,169 ha in Teterivske Forestry Enterprise (Teterivske FE) and 18,477 ha in Dniprovsko-Teterivske

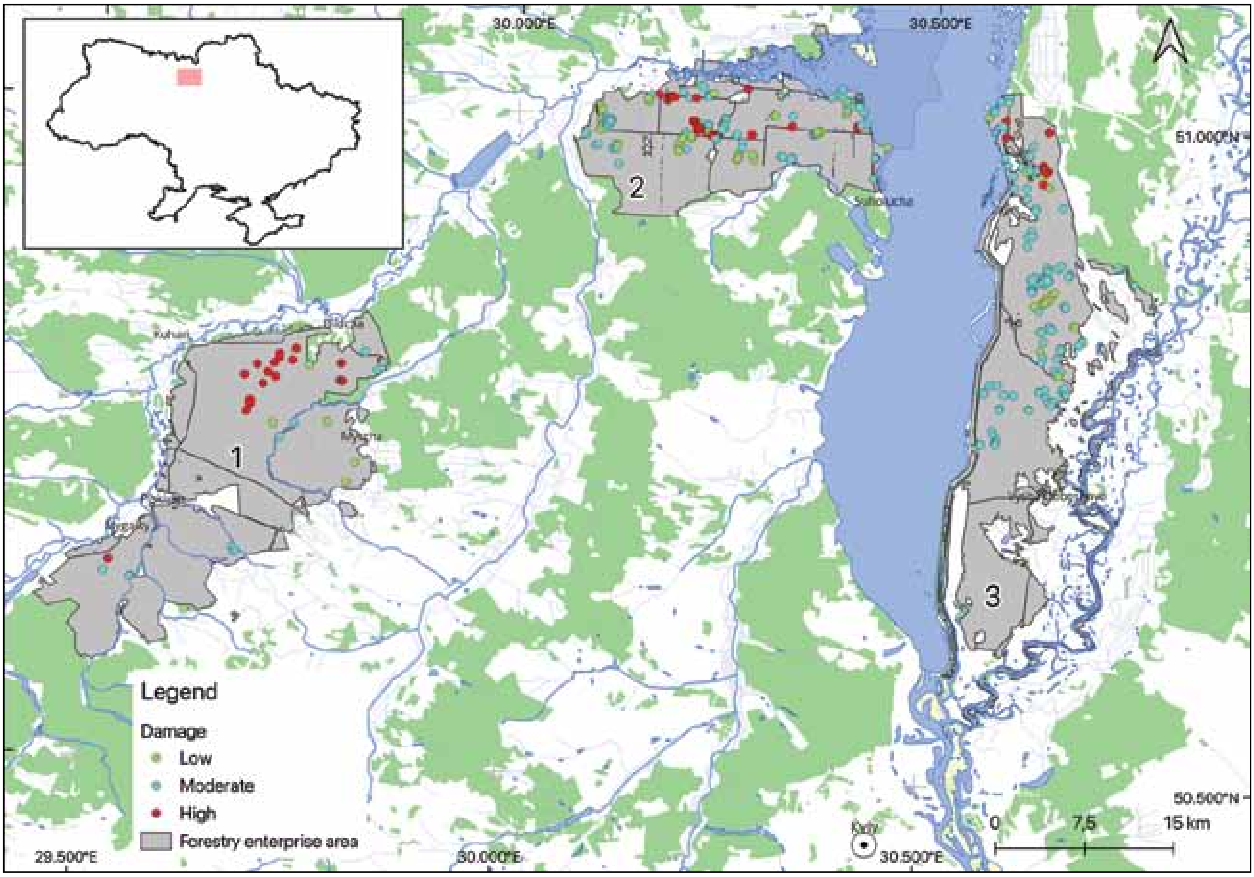

Figure 1. Location of the study area: 1 – Teterivske FE, 2 – Dniprovsko-Teterivske SFHE, 3 – Vyschedubechanske FE. Damage degree: low, up to 30% of shoots are damaged; moderate, 30–50% of shoots are damaged; high, <51% of shoots are damaged

State Forestry and Hunting Enterprise (Dniprovsko-Teterivske SFHE). Annually, the average area of young forests (up to 10 years) in these FE is as follows: 914 ha in Vyschedubechanske FE, 1,390 ha in Teterivske FE and 210 ha in Dniprovsko-Teterivske SFHE, respectively, based on their internal reporting (unpublished).

Data collection

Young forests damaged by wild ungulate animals were studied from 2015 to 2019 at the Vyschedubechanske FE, during 2015–2016 and 2018–2019 at the Teterivske FE, and the Dniprovsko-Teterivske SFHE. The age of the plants ranged from 2 to 10 years. Classification of forest site types occurring under the conditions of the Kyiv region is based on the Ukrainian typology (Migunova 1993; Bondar et al. 2020). The types of forest site conditions were designated in accordance: A_1 – dry poor forest site condition; A_2 – fresh poor forest site condition; B_1 – dry relatively poor forest site condition; B_2 – fresh relatively poor forest site condition; B_3 – moist relatively poor forest site condition; C_2 – fresh relatively fertile forest site condition; C_3 – moist relatively fertile forest site condition. Sandy soils and oligotrophic vegetation characterize Group A. Group B exhibits sandy loam soils with oligo-mesotrophic vegetation. Loamy soils and mesotrophic vegetation are distinctive for Group C.

Information on browsing young forests by ungulates was collected from the reporting of FE for the relevant period. Population estimates were obtained from annual wildlife monitoring reports provided by the forestry and hunting services. Moose, red deer and roe deer density indices reflect the average number of each species across the entire forestry enterprise area,

Table 1. Detailed information about variables according to the damage inventory data from ungulate browsing at three experimental enterprises. The number of measurements (n) represents the total number of surveyed plots. Indicators are presented in the respective mean (±SD) for the three experimental enterprises for each variable

Variables	Vyschedubechanske FE	Teterivske FE	Dniprovsko-Teterivske SFHE
	26,746.00, ha	32,169.00, ha	18,477.00, ha
Young forest area (up to 10 years old), ha	914.00	1,390.00	210.00
Percentage of young forest area, %	3.42	4.32	1.13
Number of measurements (n)	144	41	90
Area of young forests damaged by ungulates, ha	0.25 (±0.27)	0.50 (±0.46)	0.33 (±0.31)
Average age of trees, years	3.38 (±1.01)	2.85 (±1.01)	3.02 (±1.37)
Proportion of areas with damages by ungulates to the total area of young forest	0.027 (±0.03)	0.036 (±0.03)	0.159 (±0.15)
Proportion of areas with damage of the main species to the areas with damages	0.25 (±0.05)	0.49 (±0.12)	0.27 (±0.07)
Average damage degree, score	1.91 (±0.47)	2.37 (±0.77)	1.94 (±0.71)
Proportion of areas with low damage	0.026 (±0.018)	0.022 (±0.019)	0.145 (±0.129)
Proportion of areas with moderate damage	0.026 (±0.032)	0.027 (±0.022)	0.189 (±0.175)
Proportion of areas with high damage	0.041 (±0.028)	0.045 (±0.039)	0.110 (±0.071)
Moose density index	0.004	0.005	0.005
Red deer density index	0.009	0.007	0.015
Roe deer density index	0.018	0.021	0.017
Proportion of Scots pine area	0.71 (±0.01)	0.83 (±0.02)	0.68 (±0.02)
Proportion of silver birch	–	0.11 (±0.02)	0.15 (±0.02)
Proportion of English oak	0.04 (±0.01)	0.04 (±0.01)	0.17 (±0.02)
Proportion of red oak	0.23 (±0.02)	–	–

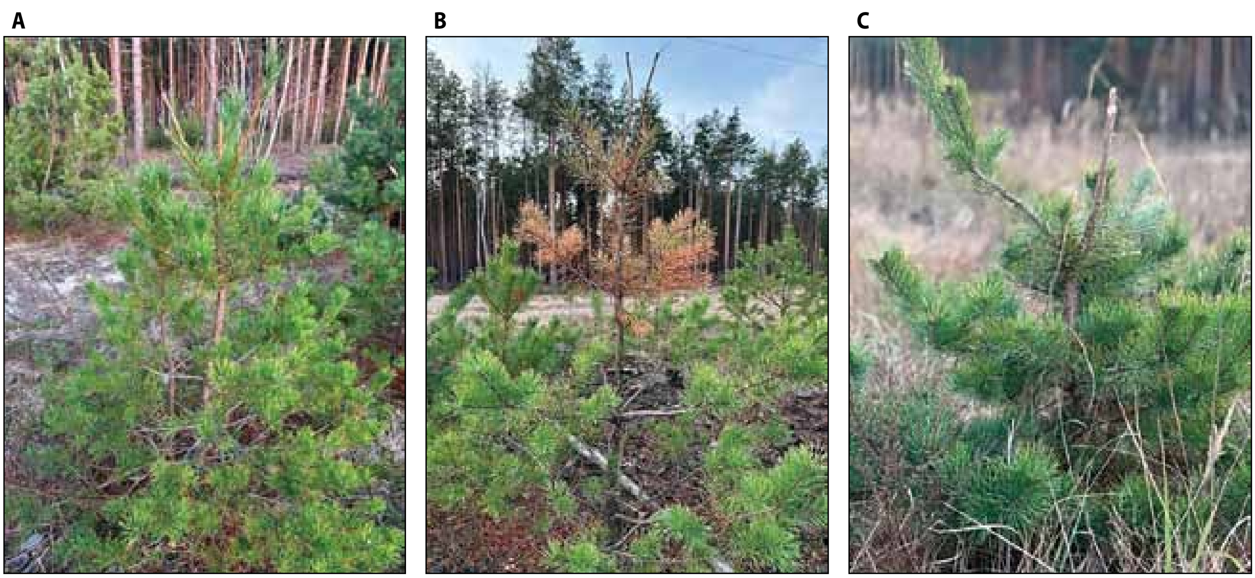

Figure 2. Photo of the damage degree in Scots pine plants: A – low, up to 30% of shoots browsed; B – moderate, 30–50% of shoots browsed; C – high, 51% or more of shoots browsed

calculated by dividing population estimates by the enterprise's total area. Information on forage availability (composition and density of plants) was taken from the relational database of forest management and the register of forest crops (unpublished) (Tab. 1).

The inventory of damages by ungulates in young forests was conducted annually in the first 10 days of March. Ten sample plots of 20 × 20 m (0.04 ha) were established at each site. The number of damaged plants and the degree of damage were assessed during the inventory. Saplings had signs of browsing on the top and lateral shoots, trunk breakage, bark gnawing or plants completely uprooted from the soil. The usage of each tree species by ungulates was assessed using a 3-point rating scale for browsing damage: 1 (low), up to 30% of shoots damaged, with signs of regeneration; 2 (moderate), 30–50% of shoots damaged, with signs of regeneration; 3 (high), more than 51% of shoots damaged, with evident signs of plant form alteration and without signs of possible regeneration (Fig. 2). Unsustainable browsing was defined as occurring when browsing damage reached 30% since it limits regeneration success and plant growth (Velamazán et al. 2017). The inventory aimed to identify trees damaged by ungulates, without recording damages caused specifically by moose, deer or roe deer.

For each experimental enterprise, we used the following indicators of the forage base: the proportion of pine, birch, English oak and red oak in the tree species composition of damaged stands and the proportion of young forests up to 10 years old to the area covered by forest vegetation. The proportion of young forests was calculated based on the area of lands covered by forest vegetation for each enterprise.

Data Analysis

To analyse the impact of ungulates on young forests, a comprehensive approach that combined statistical tests and predictive modelling was employed. For each group (enterprise), the dataset included one value per variable (Tab. 1). Open-source Python libraries (Python 3.13.0) were used for data analysis and visualization of the results. A significance level of $\alpha = 0.05$ was applied for all statistical analyses.

The preliminary data analysis included assessing the normality of distribution using the Shapiro–Wilk test, the results of which necessitated the use of nonparametric analysis methods (Shapiro–Wilk, $0.228 < W < 0.909$, $p < 0.05$). All variables related to the density of ungulates, except for the roe deer density index in the Dniprovsko-Teterivske SFHE, showed no significant deviations from a normal distribution (Shapiro–Wilk, $W > 0.909$, $0.2 < p < 0.81$).

To improve the data properties and normalize their distribution, an arcsine square root transformation was applied to each evaluation criterion expressed as a proportion. An analysis of the data before and after the transformation was conducted, confirming that this indeed enhanced the analytical properties of the data.

Nonparametric statistical analyses, specifically the Kruskal–Wallis and Mann–Whitney U tests, were employed to evaluate data that deviated from normal distribution assumptions. The Kruskal–Wallis test was applied to compare medians across three or more independent groups. The rejection of the null hypothesis, that all group medians are equal, was based on the chi-square value surpassing the critical threshold, indicating statistically significant differences among groups ($p<0.05$). The Mann–Whitney U test was utilized for comparison of two independent groups. Statistically significant differences between these groups were confirmed by p-values less than 0.05. Spearman's correlation analysis was used to examine the relationship between the plant age and the intensity of damage.

Predictive approaches for ungulate damage included the random forest model (RFM) and the generalized linear model (GLM). The dependent variable in both models is the proportion of plants damaged by ungulates. Independent variables encompassed the ungulate density index, the proportion of pine and deciduous species, plant age, the damage degree by ungulates and the forest type. Forest site types were incorporated as categorical variables in the predictive modelling process. The selection of these models was based on their ability to effectively process complex datasets and flexibility in modelling various types of dependencies (Zweifel-Schielly et al. 2009; Niyogi et al. 2021; Illanas et al. 2022; James et al. 2023).

The RFM was trained on a training set using the sci-kit-learn library (Pedregosa et al. 2011). For GLM, the binomial family with a logit link function was used, which is an approximation to beta-regression for analysing proportional data (Skorski 2024). Both models were thoroughly tested and validated. For RFM, residual analysis and feature importance visualization were used, while for GLM, coefficient estimation and statistical significance were assessed. Z-values with an absolute magnitude greater than the critical value indicate the statistical significance of the variable. P-values <0.05 are considered indicative of statistical significance in differences or the impact of a variable.

Model accuracy was assessed using the mean squared error (MSE) and the coefficient of determination (R^2) metrics for comparison model's predictions to observed data. MSE measures the average squared difference between the predicted and actual values. A low MSE indicates high model accuracy. R^2 reflects the proportion of the variability in the dependent variable explained by the model. This approach enabled us to objectively assess the impact of various factors on the damage to young forests by ungulates and to evaluate the effectiveness of the applied predictive models in the context of each enterprise.

Results

The results indicate statistically significant differences between groups (enterprises) in terms of the moose density index (Kruskal–Wallis, $\chi^2 \geq 12.57$; $p \leq 0.001$), with lower observations in Vyschedubechanske FE compared to Dniprovsko-Teterivske SFHE (Mann–Whitney U test; $p \leq 0.05$) and Teterivske FE (Mann–Whitney U test; $p \leq 0.05$), respectively. The deer density index also varied (Kruskal–Wallis, $\chi^2 \geq 12.57$, $p < 0.001$), with a lower index in Teterivske FE compared to Vyschedubechanske FE (Mann–Whitney U test; $p \leq 0.05$) and Dniprovsko-Teterivske SFHE (Mann–Whitney U test; $p \leq 0.05$). The roe deer density index also showed variation across the experimental enterprises (Kruskal–Wallis, $\chi^2 \geq 12.59$, $p < 0.001$), with the lowest index in Dniprovsko-Teterivske SFHE compared to Vyschedubechanske FE (Mann–Whitney U test; $p \leq 0.05$) and Teterivske FE (Mann–Whitney U test; $p \leq 0.05$).

There are statistically significant differences between groups regarding the proportion of damaged young forests (Kruskal–Wallis, $\chi^2 = 54.35$; $p < 0.001$). However, the difference in damage intensity is not as pronounced compared to the difference between the proportions of damaged areas (Kruskal–Wallis, $\chi^2 = 12.70$; $p < 0.05$).

The proportion of young forest areas damaged by ungulates was highest in Dniprovsko-Teterivske SFHE, statistically significantly different from the indicators in Vyschedubechanske FE (Mann–Whitney, U = 94.0, $p < 0.001$) and Teterivske FE (U = 270.0, $p < 0.001$). In Vyschedubechanske FE, more damage by ungulates was observed than that in Teterivske FE (Mann–Whitney U = 1092.0, $p < 0.05$).

The intensity of damage by ungulates was highest in the Teterivske FE, which significantly differed from the Vyschedubechanske FE (U = 1207.0, $p < 0.001$). However, the differences between the Teterivske FE and the Dniprovsko-Teterivske SFHE (U = 997.5, $p > 0.05$),

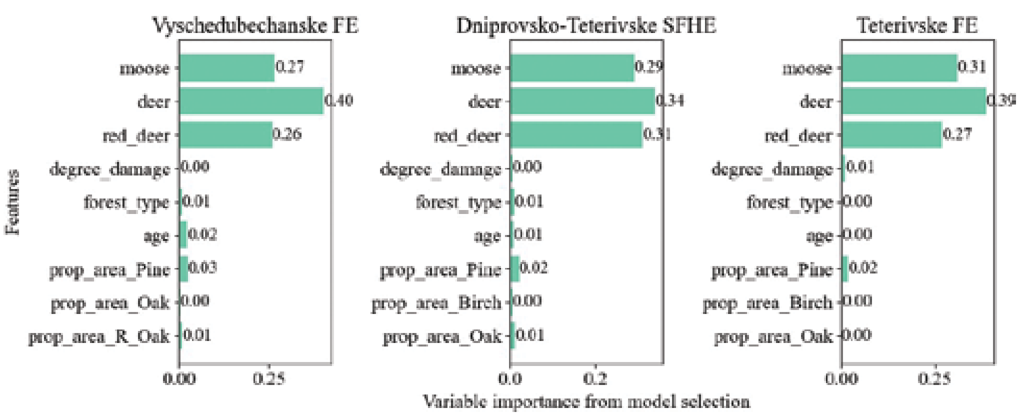

Figure 3. Scaled variable importance plot from a RFM selection process to achieve the smallest out-of-bag error for Vyschedubechanske FE, Dniprovsko-Teterivske SFHE and Teterivske FE. Panels represent the importance of variables: moose, deer, red_deer – ungulates density index; prop_area_Pine, Oak and R_Oak – the proportion of the young forest area of Scots pine, English oak and red oak. Higher values indicate increased variable importance

as well as between the Vyschedubechanske FE and the Dniprovsko-Teterivske SFHE (U = 669.5, p > 0.05), were not statistically significant.

On a regional scale, it was found that as the forest age increases, the damage degree tends to decrease slightly (n = 275, Spearman's r = -0.175; p < 0.05). Simultaneously, no statistically significant relationship was identified between the age of plants and the proportion of areas damaged by ungulates (r = -0.07, p > 0.05).

The RFM highlights significant differences in the impact of ungulate density, tree species composition, age of trees and forest type of young forests in enterprises. The most important features are related to the ungulate density: red deer (33.8–40.3%), moose (26.7–31.0%) and roe deer (25.8–29.0%). Other features are the age of trees (<2.5%), the proportion of deciduous species (<1.2%) and the forest type (<1.0%), but their impact is considerably smaller (Fig. 3).

For Vyschedubechanske FE, the SE and z-value for the intercept indicated no statistically significant impact (SE = –1.72, z = –1.49, p > 0.05) (Tab. 2). Similar results were for Teterivske FE and Dniprovsko-Teterivske SFHE, respectively, -4.66 (z = –0.214, p > 0.05) and –2.01 (z = –1.334, p > 0.05). It also demonstrates the absence of statistically significant effects. The density of ungulate populations, the age of trees, the proportion of coniferous and deciduous species, and the forest type also had no statistically significant impact on any of the surveyed enterprises (p > 0.05). The Pearson chi² and Pseudo R-squared values for each enterprise indicate low predictive power of the models regarding data variation, with the highest Pseudo R-squared value being 0.121 for Dniprovsko-Teterivske SFHE. This suggests that these variables are not strong predictors of the dependent variable or that other variables not included in the model may be more influential.

Table 2. Significance of features according to the results of the generalized linear model. Values represent model coefficients indicating the effect size and direction of each variable on the predicted degree of browsing damage

Features	Vyschedubechanske FE, n = 144			Teterivske FE, n = 41			Dniprovsko-Teterivske SFHE, n = 90		
	SE	z-value	p-value	SE	z-value	p-value	SE	z-value	p-value
Intercept	–1.72 (±1.16)	–1.49	0.14	–4.66 (±21.84)	–0.214	0.83	–2.01 (±1.50)	–1.334	0.18
Moose density	957.66 (±5276.23)	0.182	0.18	135.28 (±989.14)	0.137	0.90	–301.88 (±817.16)	–0.369	0.71
Deer density	–555.56 (±3820.72)	–0.145	0.88	17.52 (±1982.96)	–0.009	0.99	–13.39 (±58.41)	–0.229	0.82
Roe deer density	–49.84 (±442.62)	–0.113	0.91	–69.27 (±1455.44)	–0.048	0.96	179.92 (±465.09)	0.387	0.70
Age of plants	0.03 (±0.27)	0.127	0.90	0.01 (±0.95)	0.018	0.99	–0.10 (±0.27)	–0.376	0.71
Proportion of Scots pine, %	–1.03 (±0.86)	–1.202	0.23	1.23 (±13.45)	0.091	0.92	–0.005 (±1.14)	–0.004	0.99
Proportion of silver birch, %	–	–	–	1.04 (±13.66)	0.077	0.94	–	–	–
Proportion of English oak, %	–0.80 (±1.50)	–0.537	0.59	1.22 (±13.77)	0.089	0.92	–0.23 (±0.99)	–0.239	0.81
Proportion of red oak, %	–0.87 (±0.75)	–1.152	0.25	–	–	–	–	–	–
Forest type	–0.03 (±0.50)	–0.063	0.95	–0.01 (±0.72)	0.016	0.99	0.06 (±0.25)	0.224	0.82
Damage degree, score	0.005 (±0.55)	0.010	0.99	–0.06 (±0.67)	–0.090	0.93	–0.05 (±0.37)	–0.148	0.88
Pearson chi^2	0.347			0.125			0.98		
Pseudo R-squ.	0.028			0.040			0.121		

The comparison of results indicated that the choice of predictive model depends on the data specifics of the particular enterprise. The mean squared error (MSE) reflects the difference between the actual values and the model predictions, with a low MSE indicating high model accuracy. The GLM was more accurate for Vyschedubechanske FE and Teterivske FE, and the RFM was better suited for Dniprovsko-Teterivske SFHE (Tab. 3).

Table 3. Accuracy assessment of the RFM and GLM prediction models for Vyschedubechanske FE, Dniprovsko-Teterivske SFHE and Teterivske FE

Prediction models	Vyschedubechanske FE		Teterivske FE		Dniprovsko-Teterivske SFHE	
	MSE	R^2	MSE	R^2	MSE	R^2
RFM	0.0005	0.87	0.0019	0.77	0.0038	0.89
GLM	0.0003	0.92	0.0014	0.82	0.0067	0.80

Discussion

The study confirmed the existence of statistically significant differences between the groups regarding the density indices of key wild ungulates, indicating variability of ecological conditions and the impact of management practices among forestry enterprises in the Kyiv region. The proportion of plants damaged by ungulates, identified as the main variable affecting forest restoration, may be used as an indicator for establishing quotas for ungulate culling or hunting. For example, in Sweden, damage by ungulates browsing should not exceed 5% (Lindmark et al. 2020). In ecosystems with several ungulate species, it is sensible to consider all species for damage interpretation (Pfeffer et al. 2021). Different ungulate species use the territory in different ways; moose and roe deer predominantly feed on branches of trees and shrubs, while red deer have a significant portion of grass in their diet (Hofmann 1989). However, all ungulates can change their diet depending on the season or other factors (Spitzer et al. 2020).

Our results highlight the importance of selecting an adequate predictive model that considers the data specificity and conditions of the experimental territories. Using RFM and GLM revealed that each has certain advantages and limitations. RFM excels in complex scenarios with interactive factors, while GLM is better for stable data with fewer predictors (Moezzi et al. 2023). For instance, D'Aprile et al. (2020) applied GLM to study ungulate browsing preferences, finding a greater likelihood of browsing on species like *Abies, Fagus, Sorbus* and other broadleaf trees compared to *Picea*, with lower browsing on *Pinus* trees. The application of GLM in forestry research underscores the importance of statistical models in understanding wildlife-forest dynamics. It complements the predictive power of models like RFM by offering a different approach to data analysis, useful for addressing the challenges of data heterogeneity and dependence.

In our studies, the RFM demonstrated a better ability to detect complex nonlinear dependencies among many predictive variables, which is especially important for analysing ecological data where many factors are interconnected and interdependent. RFM identifies the ungulate density as the most important predictor, indicating its higher sensitivity to key ecological variables compared to GLM. However, low Pseudo R-squared values for all three enterprises suggest that not all significant predictors affecting the dependent variable were included in the model. GLM is a simpler and more interpretable model, which may be used in cases where it is necessary to clearly understand the relationship between variables and outcomes and when the interpretability of the model is more important (Song et al. 2013). Shanley et al. (2021) demonstrate that RFM performed consistently better compared to traditional resource selection function models.

Statistically significant differences in the proportion of damaged young forests in Dniprovsko-Teterivske SFHE may be related to higher density or activity of ungulates in this area. This may also be related to the fact that the enterprise's territory is limited by water space, the availability of forage resources is greater, or there is a lower level of predation, which promotes the concentration of animals in this area.

The intensity of young forest damage was high in Teterivske SF, but no similar increase in the proportion of damaged areas was observed as in Dniprovsko-Teterivske SFHE. Therefore, factors affecting the size of the damaged areas do not necessarily correlate with the frequency of such events. The damage intensity and the proportion of damaged areas are not always directly related to the ungulates density. For example, researchers in Sweden have found that the pines density in an area is a more significant factor for predicting browsing than the ungulates density (Pfeffer et al. 2021). Our research did not find a significant effect of the proportion of pine in young forests on ungulates browsing. Moreover, the deciduous species in the plots do not reduce the attractiveness of young forests for browsing.

It is also important to consider the possible impact of anthropogenic pressure, including recreational use of territories (Harris et al. 2014), which can change the behaviour of ungulates and increase or decrease the risk of damage to forests (Stankowich 2008; Pascual-Rico et al. 2021). The type of habitat also significantly affects the diet of ungulates (Zweifel-Schielly et al. 2009). The presence of more attractive plants, rather than the availability of coniferous species, explains the low proportion of coniferous shoots in the diet of roe deer and red deer in winter on agricultural lands and deciduous forests. Also confirmed is the relatively high level of use of agricultural crops in the habitats of roe deer (Spitzer et al. 2020).

The difference in factors affecting the intensity of damage to young forests in experimental enterprises indicates the need for an individual approach to each territory that requires evaluation. Common trends, such as the impact of ungulate population density on the intensity of plant damage, may be used as a basis for developing regional strategies to protect young forests from ungulate browsing. Practical application of these models in other enterprises will require detailed analysis of local conditions and data specifics, which should be included in the model. For example, if other enterprises have a different structure of forests or anthropogenic impact, this may require adaptation of the model or even the selection of another model for better predictive ability. The results of our study suggest the possible need to integrate additional variables not considered in the current analysis, such as information about climatic conditions, genetic diversity of tree species, the number of feeding points, etc.

Differences in the impact of various factors on the damage to young forests by ungulates may be related to the diversity of ecological conditions and management of forestry and hunting, including measures for the conservation and reproduction of wild animal populations, as well as hunting practices, which require further research. This indicates the need to optimize methods of managing wild animal populations, planning species composition with an increase in the proportion of deciduous tree and shrub species and implementing more effective measures to protect young forests such as fences or repellents (Stutz et al. 2019), especially during the first 5 years of cultivation. It is also important to pay attention to monitoring and data collection methods, as the accuracy and completeness of information are critical for understanding ecosystem processes and effective decision making (Niyogi et al. 2021).

Conclusions

The random forest model (RFM) outperformed the generalized linear model (GLM) in predicting ungulate browsing in young forests. Although regression analysis did not show statistically significant effects across all enterprises, RFM consistently demonstrated higher predictive accuracy, highlighting its value for forest damage assessment in areas with high ungulate populations.

Ungulate density was identified as the primary driver of damage, while tree species composition, age and forest type had limited influence. Results indicate that browsing intensity decreases with tree age, suggesting the need for protection measures for young forests, especially within the first 5 years.

The study underscores the importance of monitoring ungulate populations, assessing forest conditions and developing adaptive management strategies to safeguard young forests and promote long-term resilience.

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