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Are Trees Planted along the Roads Sustainable? A Large-Scale Study in the Czech Republic

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Abstract: Trees provide a wide variety of ecosystem services to society and form the character of the environment and landscape. The analyses of tree populations and their resistance to changing conditions related to climate change typically focus on urban tree communities or forest trees. Similar studies on non-forest trees in the open landscape are largely missing; even the evidence on tree species abundance and distribution is sporadic. The article aims to expand the current evidence by a large-scale study on roadside trees in the Czech Republic. Using an extensive dataset that covers 91.2% of the total tree population along roads in nine NUTS3 regions, we assess the state and observed practices in selecting tree genera for roadside planting and discuss the implications for sustainable tree planning and management. Our survey documented 133,169 tree individuals belonging to 116 species and 40 genera. The results show that 75% of the total roadside plantings along second-class motorways and first-class roads are represented by seven main genera of deciduous trees (*Acer*, *Fraxinus*, *Tilia*, *Malus*, *Betula*, *Populus*, and *Quercus*), the distribution of which is similar across most Czech regions. New plantings have shifted only a little from the original species distribution. Traditional roadside species are becoming a more popular choice among new plantings, and the effort not to let the invasive trees outgrow into the mature stage is apparent. Most of the original and newly planted species are relatively suitable for emerging risks related to climate change. To achieve more sustainable patterns in roadside tree species composition in the future, especially the susceptibility of some commonly planted roadside tree species to emerging pests and diseases (e.g., *Fraxinus excelsior*) and to unfavorable site conditions typical for roadside tree stands (*Tilia cordata*) is of relevance to tree managers. The relative abundance of tree genera was proven to be similar in most studied regions, which makes the recommendations equally relevant for roadside tree managers across the country.

Keywords: roadside vegetation; tree management; tree composition; species distribution; climate change; pests and diseases; resilience of vegetation

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Citation: Mácová, K.; Szórádová, A.; Kolařík, J. Are Trees Planted along the Roads Sustainable? A Large-Scale Study in the Czech Republic. *Sustainability* **2022**, *14*, 5026. https://doi.org/10.3390/su14095026

Academic Editor: Tan Yigitcanlar

Received: 21 March 2022
Accepted: 19 April 2022
Published: 22 April 2022

1. Introduction

Sustainable selection of species for planting is a multifaceted concept, reflects a variety of motivations, and involves a wide array of different practices in landscape design [1,2]. Within this concept, optimal selection of tree taxa refers to selecting well-adapted tree species that help form a self-sustaining landscape that can persist and are manageable in the long term with low resources (water, nutrients, carbon expenditures, or maintenance time and cost) and provide the desired level of ecosystem services such as support of native biodiversity, being attractive to local people or reinforcing the character of the landscape and attain these benefits in the long term [1–3]. Tree planting is critical for a sustainable future as it can slow the climate crisis by capturing CO_2 and help restore landscapes and their microclimate; on the other hand, trees are affected by climate-related stresses, which alter their self-sustaining abilities in the landscape. Other concerns related to achieving sustainable tree communities are linked to specific growing environments and microclimates that impact planting conditions and survivability of plant materials [2,4];

and to competition among native, non-native and invasive species [1,2,4]. Each landscape site offers a variety of specific local site growing environments, but regarding the roadside environment, these are typically defined by potentially difficult conditions. Sustainable tree planting of well-adapted tree species should ensure a tree's vitality, benefits, and longevity, even in an unfavorable environment [3,5].

1.1. Aspects of Roadside Tree Planting for Species Selection

Trees along roads represent non-forest woody vegetation which significantly contributes to the formation of the landscape. There is a number of studies that point to overall positive aspects of the presence of trees in the landscape [6,7]. Other studies stress out particular benefits of roadside trees such as the provision of a habitat for animals [8], significant reduction of noise levels and concentrations of particulate matter and other gaseous air pollutants emitted by vehicle activity on the nearby road [9,10], windbreak or cooling effect contributing to better microclimate along the roads [11], reduction of CO_2 in the atmosphere by fixing carbon during photosynthesis, or contribution to aesthetically pleasing landscape character including positive influence on the human psyche, including stress and fatigue restoration not limited to drivers [12,13].

The positive aspect of trees also drives the species selection by tree managers. In the case of the Czech Republic, mature vegetation along the roads has formed the character of the landscape for centuries [14]. The deliberate creation of greenery along the roads in the area of the current Czech Republic has been documented from the 18th century on. Tree species choices for planting along important roads were then mostly driven by aesthetic, orientational, or other reasons rather than direct economic gains from trees. Linden, horse chestnut, maples, or poplars were used in particular [15]. On the contrary, fruit trees prevailed among tree plantings along roads of minor importance in the past. In 1958, 25% of all fruit trees were concentrated in alleys near the roads [16]. Some of these old trees and historical tree alleys have remained maintained up to the present.

Nowadays, other criteria for the selection of tree taxa to be planted along the roads also have to be accounted for. Most important for the Czech tree roadside managers are probably the safety aspects of road use during the whole lifetime of the tree. Roadside trees may be associated with a significant level of risk if they form a solid obstacle and reduce the view of drivers, and also the risk of breaking off part of the crowns or falling whole trees onto areas with a high frequency of use may not be negligible. Further essential criteria for contemporary roadside plantings include taxon resistance to salinity, native origin, and invasiveness, or susceptibility to diseases and pathogens [17,18], including the spread of non-native pests and pathogens from other climatic regions; or adequacy to specific landscape character [19]. Compared to tree stands in the open landscape, many tree stands along the roads are characteristic of extreme conditions challenging the growth, health, and survival of the individual trees. Simultaneously, the management of roadside vegetation has an umbrella effect on the biodiversity levels and composition of plant and animal species [20].

Landscape managers have to take into account that in the future, even more strenuous conditions are expected under the scenarios of increased temperature and intensified weather extremes [21,22]. When altering both the abiotic stresses and the range of infecting organisms or plant invasions, climate change is expected to influence tree abundance, distribution, and health. All these patterns may accelerate into a significant loss of ecosystem services provided by roadside trees.

On the other hand, tree plantings along the roads can prove rather difficult and costly to maintain, considering the extreme characteristics of their tree stands compared to trees planted in other landscape settings. Roadside vegetation inventories and vegetation management, as well as a prudent choice of tree taxa for new roadside plantings, have become increasingly important to maintain the ecosystem services provided by these tree communities. However, analyses of tree populations and their resistance to changing conditions related to climate change typically focus solely on urban tree communities or on forest tree stands. Similar studies on non-forest trees in the open landscape are largely missing; even the evidence on tree species abundance and distribution is sporadic. The unavailability of even basic data further hampers the assessment of ecosystem services provided by roadside trees.

1.2. Research Objectives

The article aims to expand the current evidence by a large-scale study on roadside trees in the Czech Republic. The objectives of the study are: (a) to analyze the species composition of roadside tree communities across the country; and to discuss the implications of (b) whether the patterns in newly planted trees favor the sustainability of tree management; and (c) how resilient the roadside tree populations appear with respect to the risks posed by the abiotic environment and emerging pests and diseases. The results will facilitate the sustainable management of tree populations. The data from this study also enable subsequent analyses on ecosystem services associated with roadside trees or future quick scans of the potential effects (cost or damage estimates) of pests or diseases newly emerging in the future.

To our best knowledge, this is the first study employing such a large dataset on this topic that can aspire to yield representative results on non-forest tree species inventory, both in the Czech and in the international context. The last Czech evidence is limited to a study focusing on vegetation (trees, shrubs, and herbs) along several particular motorways [23]; and another article that addressed new plantings of trees in different land use contexts in non-forest settings [24]. Foreign studies account only for a limited number of articles (e.g., recent studies [25,26] in Asia; in Europe, e.g., studies [27,28]), all of which focused solely on the urban environment. Only a few of the above-cited studies [24,25,27] incorporate at least a short discussion of the implications of sustainable tree management.

2. Materials and Methods

2.1. Study Area

The study focuses on the Czech Republic, a country located in Central Europe, in the moderate climate zone with fluctuating average annual temperatures. Its area of 78,870 km^2 is dominated by a hilly plateau surrounded by mountain ranges along the borders. The average altitude is 450 m. As in majority of Western and Central European countries, the most widespread biome is broad-leaved deciduous forest.

The road network in the country is very dense. We analyze roadside trees accompanying major categories of roads, specifically along motorways of 2nd class and on 1st class roads as defined by the Road act no. 13/1997 [29]. All these trees are state-owned, and their management is administered by the Road and Motorway Directorate, which is a state contributory organization founded by the Ministry of Transport of the Czech Republic. First-class highways and third-class roads that are at lower position in the road classification are not included in the analysis due to data unavailability.

2.2. Tree Inventory Data

In the study, we focus on trees planted out of forest as trees in alleys or solitary growing individuals. Both trees in open rural landscape that are part of the treeline and solitary growing individuals within approximately 10 m from the road edge were recorded.

The data on roadside trees were recorded in sufficient quantity for 9 out of total 14 NUTS3 regions in the Czech Republic (see Figure 1; the abbreviation NUTS stands for Nomenclature of territorial units for statistics by Eurostat). For the remaining five NUTS3 regions, the data are not in quantity allowing us to draw any general conclusions—we, therefore, exclude all the data on these five regions from the data analysis.

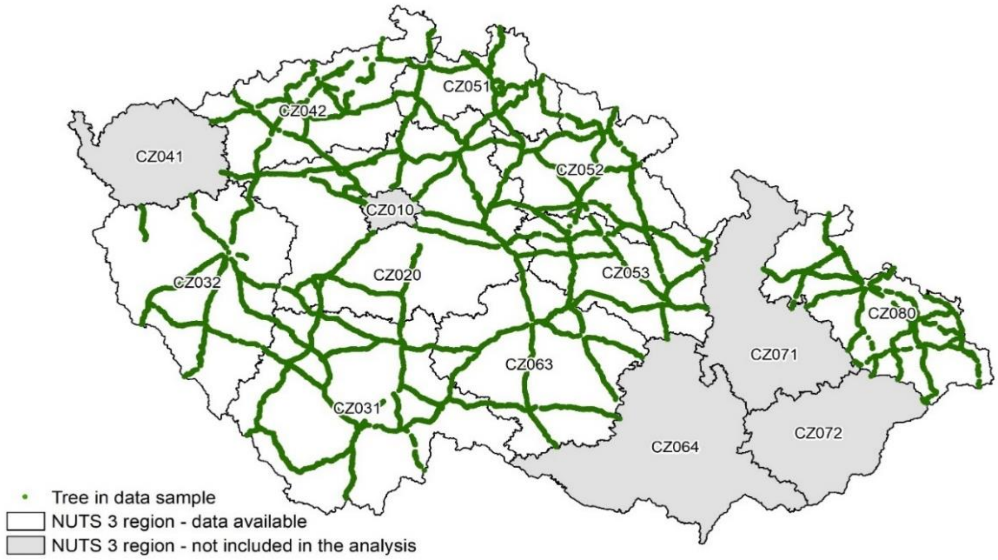

Figure 1. Study area (nine NUTS3 regions in the Czech Republic) and geographical position of the final data (n = 133,169 trees). Basemap: State Administration of Land Surveying and Cadastre 2020.

Data collection was carried out in years 2015–2020 and is part of the database www.checktrees.com (accessed on 19 April 2022). A total of 4922 km of roads in 9 NUTS3 regions were fully inventoried, which accounts for 91.2 % of all motorways of 2nd class and 1st class roads in these regions. In total, 133,169 trees were individually evaluated. The location of all trees in the data sample is depicted in Figure 1. For each tree, its geographical position, species (and cultivar if applicable), and category of physiological age (new plantation or older trees representing the original roadside tree population) were determined. In case of *Malus* genera, trees are not further distinguished into species (for example due to tree inventory timing to winter). Further dendrometric parameters such as tree height, trunk diameter, vitality, and health status are not of the focus of this study as these were determined for a minority (16%) of the total sample—only for trees important regarding their size, species, and location.

2.3. Data Analysis

The sample represents vast majority of the population of roadside trees in the study area. Generally, the sample size should not exceed 10% of the original population data to allow unbiased testing of such hypotheses [30]; on the contrary, our sample represents >90% of the population of roadside trees in 9 regions. For the conclusions related to the whole sample, the descriptive statistics and relative frequencies are therefore sufficient in our case. Further statistical testing usual in other studies is aimed at drawing conclusions on the distribution of population parameters (distribution of tree characteristics in the population, relative abundance of species, genera, etc.) from the analysis of a limited sample drawn from the population, which would not make much sense for this study as stated above.

Panel data are not available for a majority of the sample, which is usual in similar studies. The study is designed as cross-sectional, where each observation represents the most actual information on the specific tree.

Correspondence analysis was used to visualize similarities and differences in relative abundance of tree genera across the 9 regions of the country. Trees along analyzed major categories of roads are managed regionally, which means that analysis by NUTS3 regions is the most intuitive for this study. Chi^2 test was performed to test the statistical significance of tree genera distribution in a region compared to the whole sample. Data management and analysis were conducted using a standard software package (Stata, version 15.0, StataCorp, College Station, TX, USA).

3. Results and Discussion

3.1. Actual Taxonomic Composition of Trees

3.1.1. Tree Genera

Among the total of 133,169 trees that have been assessed, we have identified 40 genera in total (Table 1). The most frequently represented genera were *Acer* spp. (18.82%), *Fraxinus* spp. (13.17%), *Tilia* spp. (12.88%), *Malus* spp. (11.46%). These four genera account for 56% of the trees along motorways of second class and on first-class roads in the analyzed nine NUTS3 regions. Other commonly planted species exceeding the 5% threshold of occurrence are *Betula* spp. (6.96%), *Populus* spp. (5.83%) a *Quercus* spp. (5.65%). These seven most common genera form as much as 75% of the total roadside plantings.

Table 1. Genera identified in the data sample (n = 133,169).

Threshold (by % of Relative Abundance)	Genera	Share in %
>10%	*Acer*	18.82
	Fraxinus	13.17
	Tilia	12.88
	Malus	11.46
>5%	*Betula*	6.96
	Populus	5.83
	Quercus	5.65
>1%	*Sorbus*	3.30
	Prunus	2.95
	Pyrus	2.82
	Salix	2.66
	Cerasus	2.53
	Pinus	1.75
	Juglans	1.56
	Aesculus	1.44
	Picea	1.36
	Alnus	1.30
>0.1%	*Robinia*	0.96
	Crateagus	0.71
	Ulmus	0.58
	Larix	0.36
	Carpinus	0.30
	Fagus	0.13
>0.01%	*Thuja*	0.09
	Corylus	0.06
	Pseudotsuga	0.06
	Padus	0.05
	Platanus	0.04
	Rhus	0.04
	Catalpa	0.03
	Chamaecyparis	0.03
	Juniperus	0.03
	Hippophae	0.03
	Aronia	0.023
	Abies	0.018
	Ailanthus	0.014
	Taxus	0.011
>0.001%	*Armeniaca*	0.008
	Eleagnus	0.007
	Castanea	0.005
	Total	100

Out of the fruit tree species that have historically accompanied minor roads in the Czech landscape (*Malus*, *Prunus*, *Cerasus*), only *Malus* is frequent around studied roads of higher importance. Among the less frequent genera, *Ulmus* spp. makes up only 0.58% of the recorded trees. This is probably a consequence of a mass decline of elms in the 1960s and 70s associated with *Ophiostoma novo-ulmi* [31].

Since particular regions are characterized by different landscapes, which may be reflected in tree composition along roads [19], we further investigate similarities and differences in roadside tree composition among NUTS3 regions. The analysis is performed for the seven most common genera that are probably most important from the point of view of tree management efforts regarding their abundance.

According to the results (Table 2), the minimal and maximal representation of these genera differs by up to cca five or ten percentage points from the average distribution in all nine regions.

Table 2. Genera identified in the data sample for particular NUTS3 regions of the Czech Republic (share in %, n = 133,169).

NUTS3 Region	NUTS3 Code	*Acer*	*Fraxinus*	*Tilia*	*Malus*	*Betula*	*Populus*	*Quercus*	Chi^2 Test (df = 6) [1]
Prague	CZ010				(data not available)				
Central Bohemian Region	CZ020	21.1	10.6	14.0	10.5	4.7	5.5	5.3	1.7
South Bohemian Region	CZ031	18.6	13.0	14.7	12.1	8.3	5.2	8.7	2.3
Plzeň Region	CZ032	15.2	8.1	7.2	26.6	4.7	5.5	10.4	29.9 ***
Karlovy Vary Region	CZ041				(data not available)				
Ústí nad Labem Region	CZ042	22.0	14.8	4.2	8.3	4.6	8.4	4.0	10.0
Liberec Region	CZ051	14.1	12.5	9.3	14.4	7.0	4.9	9.9	6.3
Hradec Králové Region	CZ052	24.1	18.0	12.6	5.2	5.6	7.2	2.8	8.7
Pardubice Region	CZ053	20.8	11.8	15.3	13.4	8.5	3.1	2.5	4.5
Vysočina Region	CZ063	13.5	16.7	19.6	7.0	12.9	5.4	2.5	14.5 **
South Moravian Region	CZ064				(data not available)				
Olomouc Region	CZ071				(data not available)				
Zlín Region	CZ072				(data not available)				
Moravian-Silesian Region	CZ080	10.1	14.9	10.4	13.4	6.7	10.1	4.3	8.6
Total average		18.8	13.2	12.9	11.5	7.0	5.8	5.6	
Minimum		10.1	8.1	4.2	5.2	4.6	3.1	2.5	
Maximum		24.1	18.0	19.6	26.6	12.9	10.1	10.4	

[1] Asterisks indicate significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Correspondence analysis ([32]; Figure 2) is used to further visualize the patterns in the relative abundance of most frequent genera across regions. The first ordination axis included 51.7% of the data variability, and the second included 25.8%. Data on the actual abundance in particular regions (labeled with suffix −1 in Figure 2) suggest that most regions are not very different in terms of the relative distribution of the seven most common genera from the others. Three regions visually stand out: (1) in the Pilsen region (NUTS3 code CZ032), more than a quarter (27%) of all trees along the two analyzed types of roads are formed by the genus *Malus* and every 1 in 10 trees is an oak *(Quercus)*; (2) in the Vysočina region (CZ063), the genus *Betula* is represented twice as much compared to the average representation and the proportion of linden trees (genus *Tilia*) is also significantly above the national average; and (3) the Ústí nad Labem region (CZ042) is distinguished from the other regions by relatively high abundance of *Populus* and *Acer*.

Finally, using Chi^2 goodness of fit statistics (Table 2), we test whether the proportions of the seven most common genera in the roadside tree population of each region are equal to their total distribution in the whole sample (9 regions). The null hypothesis (equality of proportions of tree genera) is rejected only for two regions: the Pilsen region (CZ032) and the Vysočina region (CZ063). To sum up, the available data on tree diversity do not suggest that there are large differences among most regions that would spatially distinguish the tree management needs (or the visual experience of the drivers) throughout the country.

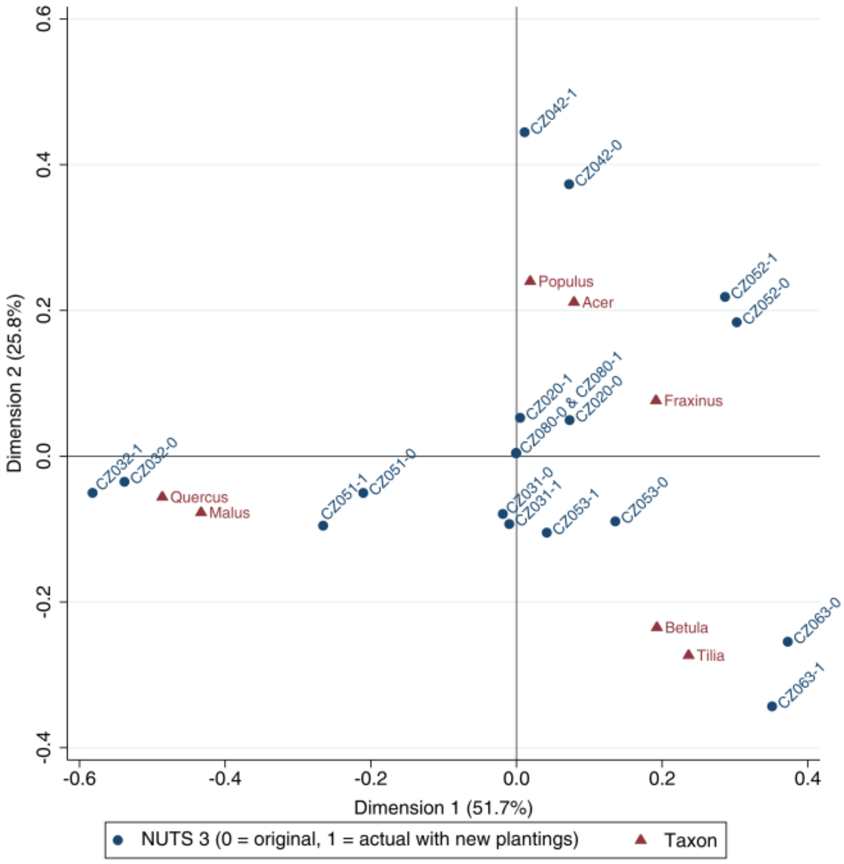

Figure 2. The first two axes of the correspondence analysis for seven most common roadside tree species in the study area in NUTS3 regions (see Table 2 for NUTS3 codes and species distribution), both for the original composition of tree species in the region not including new plantings (NUTS3 codes labeled with suffix 0) and actual composition incorporating original roadside tree population and new tree plantings (NUTS3 codes labeled with suffix 1).

3.1.2. Tree Species

To be able to assess the overall resiliency or magnitude of risks related to the roadside tree population for the study site, also the abundance of particular tree species is determined. A total of 116 tree species were determined along the roads in the data sample, which roughly corresponds to the last study that dealt with road vegetation in the Czech Republic [23], where 126 species of woody plants were recognized.

Following the abundance of species by the most frequent genera (Table 1), the most frequent genus in the sample, *Acer*, consists of 42.3% *Acer platanoides*, 39.7% *Acer pseudoplatanus*, 13.2% *Acer negundo*, 2.7% *Acer campestre*, 2.0% *Acer saccharinum* (and other species and their cultivars representing the *Acer* genus not exceeding 2%). *Fraxinus* is a genus with the second-largest occurrence composed of 95.1% *Fraxinus excelsior* and 4.7% *Fraxinus pennsylvanica*. The third most numerous genus *Tilia* consists of 77.3% *Tilia cordata*, 21.6% *Tilia platyphylos*, and 0.8% *Tilia x euchlora* (and other less frequent species). For *Malus* genera, the exact species were not determined.

If the tree species composition is analyzed by species (Table 3), the results are similar to those drawn from the analysis of tree genera (Table 1 and Section 3.1.1.). The most numerous species were *Fraxinus excelsior* (12.52%), *Malus* spp. (10.7 %), *Tilia cordata* (9.96%), *Acer platanoides* (7.97%), *Acer pseudoplatanus* (7.47%), *Betula pendula* (6.96%) and *Quercus robur* (4.72%).

Table 3. Tree species identified in the data sample (*n* = 133,169; species with lower share than 0.02% are not shown).

Threshold (by % of Relative Abundance)	Tree Species	Share in %
>10%	*Fraxinus excelsior*	12.52
	Malus spp.	11.46
>5%	*Tilia cordata*	9.96
	Acer platanoides	7.97
	Acer pseudoplatanus	7.47
	Betula pendula	6.96
>1%	*Quercus robur*	4.92
	Sorbus aucuparia	3.05
	Pyrus communis	2.82
	Tilia platyphyllos	2.79
	Acer negundo	2.48
	Cerasus avium	2.42
	Populus nigra	2.35
	Populus x canadensis	1.84
	Juglans regia	1.54
	Salix caprea	1.49
	Prunus domestica	1.44
	Aesculus hippocastanum	1.43
	Pinus sylvestris	1.31
	Alnus glutinosa	1.29
	Prunus insititia	1.25
>0.1%	*Robinia pseudoacacia*	0.96
	Populus tremula	0.93
	Salix alba	0.81
	Picea abies	0.77
	Crataegus laevigata	0.62
	Fraxinus pennsylvanica	0.62
	Picea pungens	0.50
	Acer campestre	0.50
	Quercus rubra	0.44
	Acer saccharinum	0.37
	Larix decidua	0.36
	Pinus nigra	0.35
	Populus suaveolens	0.31
	Carpinus betulus	0.30
	Salix fragilis	0.29
	Ulmus laevis	0.24
	Quercus petraea	0.21
	Ulmus glabra	0.18
	Ulmus minor	0.16
	Populus alba	0.13
	Populus nigra	0.13
	Fagus sylvatica	0.13
	Sorbus aria	0.13
	Sorbus intermedia	0.12
	Prunus cerasifera	0.11
	Tilia x euchlora	0.11
	Populus simonii	0.11
>0.02% (in alphabetical order)	*Alnus incana*; *Aronia melanocarpa*; *Catalpa bignonioides*; *Cerasus serrulata*; *Corylus avellana*; *Corylus colurna*; *Crataegus monogyna*; *Fraxinus ornus*; *Hippophae rhamnoides*; *Chamaecyparis lawsoniana*; *Juglans nigra*; *Juniperus communis*; *Padus avium*; *Picea glauca*; *Picea omorika*; *Pinus heldreichii*; *Pinus mugo*; *Pinus strobus*; *Platanus x hispanica*; *Populus balsamifera*; *Prunus spinosa*; *Pseudotsuga menziesii*; *Quercus palustris*; *Rhus typhina*; *Salix matsudana*; *Salix x sepulcralis*; *Thuja occidentalis*; *Tilia tomentosa*	

Roadsides are a key component of the landscape and, especially in cultural landscapes, can have high conservation value [33], which is also apparent in this study. Most species determined along the roads in the data sample are native and align well with the historical traditions of roadside tree planting.

On the other hand, roadsides may effectively facilitate plant invasions [34,35] and the dispersal of non-native plants, negatively affecting surrounding natural and semi-natural communities. Such species include e.g., *Ailanthus altissima*, *Acer negundo*, *Robinia pseudoacacia* [36,37]. Some non-native tree species may be, on the other hand, perceived by tree managers as more resilient to the adverse environment of the road bands. According to Table 3, less than 6% of trees in the sample can be indicated as non-native in the Czech Republic. In our sample, the invasive species *Acer negundo* accounted for 2.5%, *Robinia pseudoacacia* 1.0%, and *Ailanthus altissima* did not even exceed 0.05% share among the data. As positive as this finding may seem at first, it is important to underline that this study focuses only on tree individuals, while these species often form a shrub layer, and, therefore, all individuals need not be fully captured in our sample. The last analysis of selected first-class highways in the country [23] also included a shrub layer and reported that a serious proportion of woody species along the roads in the sample (40%) were species non-native in Central Europe. From our sample of roadside trees, it can be nonetheless concluded that the effort not to let the invasive tree individuals outgrow into the mature stage is rather evident in the whole pilot area.

3.2. Trends in Species Selection for Roadside Plantings

Out of the total evaluated tree population in all regions, 16.8% were represented by newly planted trees (tree plantings). The composition of new plantings along roads in the last 5 years (2015 to 2020) shifted a bit from the overall tree species composition. The most common genera among the new plantings are *Acer* spp. (23.3%), *Fraxinus* spp. (16.2%), *Tilia* spp. (15.8%), *Quercus* spp. (7.8%), *Sorbus* spp. (6.4%), *Prunus* spp. (3.7%), *Malus* spp. (3.6%) and *Cerasus* spp. (3.3%). Other genera (including *Betula* and *Populus*) are less frequent among new plantings and did not exceed 3% of abundance. The first five above-mentioned genera compose 76% of the new plantings. In comparison with Table 1, which addressed all roadside trees in the sample, it is evident that the species pattern among the new plantings is still relatively similar and only shifts a little in favor of the already most abundant genera. Some exemptions include *Sorbus* and *Prunus,* which have been lately planted more frequently than what would correspond to their general representation among roadside trees in the sample (Table 1). On the other hand, *Populus* and *Malus* are on the decline among new roadside tree plantings. Soft poplar wood is more prone to breaking off skeletal branches, which can pose an increased risk to road safety. This fact may be the reason for the reduction of *Populus* presentation in the taxonomic composition. The population of *Betula* trees in the sample (Table 1) accounts mostly for alleys and purposefully planted solitary trees, not so much for spontaneously developed individuals of this pioneer species. Short lifespan together with poor compartmentalization are probably the main two reasons why *Betula* spp. does not commonly appear among new plantings.

The most frequently planted species among the new tree plantings are *Fraxinus excelsior* (15.9%), *Tilia cordata* (11.4%), *Acer pseudoplatanus* (11.0%), *Acer platanoides* (9.2%), *Quercus robur* (7.4%), *Sorbus aucuparia* (5.8%), *Tilia platyphyllos* (4.3%) and *Malus* spp. (3.6%). Other species identified among newly planted trees along the studied types of roads are less frequent than 3%. These results suggest that there is an obvious effort to continue the historical trends of planting native tree species along the studied types of roads, i.e., species suitable in terms of cultural and ecological continuity. Historically popular fruit tree genera are nonetheless slightly underrepresented in the new plantings compared to their original abundance.

However, Figure 2 suggests that the choices of species for new plantings in the last 5 years have not (yet) dramatically affected the similarity of particular regions to other regions (data points related to original tree composition without new plantings are labeled with suffix -0 in Figure 2). For the most distinguished regions (see Section 3.1), species selection choices favor the tree genera that make the region characteristic compared to others. If these trends also continue in the future, the roadside trees in these regions may differ in terms of relevant tree management risks related to climate change (see Section 3.2.) and ecosystem services provided by trees (such as aesthetics, effects on microclimate through shading and cooling, CO_2 sequestration or production).

3.3. Resilience of Roadside Tree Populations

The often difficult abiotic conditions of the tree stands along communications (restricted soil volume, unfavorable chemical composition of soil including de-icing salt and lack of nutrients, restricted water availability) and susceptibility to pests and diseases has to be accounted for in species selection of new plantings to achieve more sustainable patterns in roadside tree species composition. In combination with climate change effects such as droughts or heatwaves, the future resilience of tree populations to these factors can be even more limited [3,5,38,39]. Among other climate change impacts, also wind loads and windthrows are of high relevance for the open landscape around communications, accentuating the future trade-offs between social benefits provided by trees and road safety.

Under the perspective of climate change, potential poor or incorrect roadside tree choices may be increasingly related to the unsustainability of whole tree populations. Several tree taxa that are abundant in the pilot area are sensitive to at least one of these factors. This may affect roadside tree populations in the future, reduce tree health and lifespan and increase tree mortality, and lead to the incapability of these habitats to provide the nowadays usual level of ecosystem services supportive of quality of life, and in economic terms, to the ultimately larger management of costs necessary for tree maintenance, removal, or replacement.

When selecting suitable taxa for the vegetational accompaniment of roads, it is necessary to consider specificity related to road maintenance and tolerance to the salt content. The small-leaved lime (*Tilia cordata*), which is sensitive to saline soils [18,40], is the second most commonly planted taxon. On the contrary, other very frequently planted taxa such as European ash (*Fraxinus excelsior*), sycamore maple (*Acer pseudoplatanus*), English oak (*Quercus robur*), and Norway maple (*Acer platanoides*) tolerate salination relatively well.

Perhaps the most important problem is associated with dieback of European ash (*Fraxinus excelsior*) caused by *Hymenoscyphus fraxineus* (T. Kowalski) Baral, Queloz, and Hosoya. This is relevant for a large number of European countries [41,42], the Czech Republic being no exception. The first occurrence in this country was confirmed in 2007 [42], and, currently, the pathogen is widespread throughout the whole country area. European ash (*Fraxinus excelsior*) is one of the most common species found along the main roads in the study site (12.5% of all tree plantings—Table 3), and its popularity is increasing among new roadside plantings. It is also one of the most frequently planted species among all new non-forest tree plantings in the Czech Republic in all landscape settings [24]. Similar problems in the Czech Republic encountered mostly at the local level are associated with the presence of *Euproctis chrysorrhoea* on *Malus* and *Tilia* trees and with various species of *Yponomeuta* genus. These are relevant mainly for fruit trees along roads, which are also very abundant.

Special attention must be paid to the presence of wood fungi in the trees around roads due to their possible effect on the stability of the trees and the increased risk of their failure. For this reason, well-compartmentalizing species should be preferred due to their better ability to withstand long-term colonization. The most numerous species, *Fraxinus excelsior*, as well as *Tilia cordata*, *Acer pseudoplatanus*, or *Quercus robur,* are well-compartmentalizing species. On the other hand, species with poor compartmentalization include: *Malus* spp., *Acer platanoides*, *Betula pendula*, *Sorbus aucuparia*, *Populus* spp., and *Salix* spp. are common in the study area as well. Another option is small crowned species, in which the risk of overloading in cases of external wind load is significantly reduced.

Drought stress and temperature changes, including heatwaves, are among the most challenging climate-related stressors affecting tree physiology [5,39,43–45]. For common tree species, drought stress adaptation potential is usually known or assumed for species by their origin (from dry regions or ecotypes from dry locations). Species-specific ability to cope with environmental stresses stems from ecological considerations, and, therefore, the response of particular species varies by a period of drought occurrence (especially spring or summer droughts can be problematic), duration, or repetition of drought periods. It further depends on local conditions, such as soil type and water storage capacity. Furthermore, dry air and wind aggravate the drought stress. Common impacts that affect the present or future magnitude of most ecosystem services provided by the tree in the pilot area include partial defoliation, leaf scorching, crown changes, immediate or delayed reductions in tree growth, or dieback (mostly of young trees). Future changes in precipitation patterns, periods of droughts, and temperature changes (heat waves) affect more or less all tree species from mesophytic forests with high water use [5,44]. Nonetheless, as there is no single and ultimate measure of drought stress [39], the results and recommendations may vary across different landscape settings [43–46] and may shift over time [45], while the scientific evidence on (particularly long-term) drought stress of tree populations is far from sufficient [39,46].

Among the more frequent species in the pilot area, the combination of the above-mentioned factors may affect particularly the numerous populations of *Tilia* and also other species thriving in moister areas (e.g., *Sorbus aucuparia*). *T. cordata* is generally considered a moderate drought-tolerant species [5,43], certainly in forests [45], but it is problematic to cope with longer periods of water deficit or under several combined stressors in urban environments [3,18,44]. Then, irrigation of not only young but, in some cases, even mature *Tilia* trees may be one of the possible ways [38] how to sustain the needs of this large-crowned tree, which may pose a future problem at numerous impervious tree stands along roads.

To conclude, we find that both the original composition of trees and the new plantings are largely suitable for the extreme characteristics of tree stands along the roads. However, the general recommendation on species selection for planting resilient roadside tree communities is to shift from the still increasingly popular *Fraxinus excelsior* to species more resilient to actual pathogen threats. Such species encompass *Acer pseudoplatanus* (or also *Acer campestre,* which is not frequently planted at present) or *Quercus* spp. These species may help build more resilient roadside tree communities, as they are well-compartmentalizing, tolerate salinity, and are moderately resistant to drought. *Tilia* spp. (especially *Tilia cordata*), is nowadays a popular choice for new roadside plantings in the study site, is a less prospective specie sensitive to several stressors. The specific choices, of course, have to conform also to the particular locality and technical situation.

On the other hand, tree management should not stick only to these several above-mentioned species. It is essential to maintain the high species diversity of roadside tree communities so that the complex greenery along roads provides a wide range of ecosystem services and is more resilient to potential new issues emerging in the future [39]. We also highly recommend re-evaluating the list of issues affecting the tree population resilience presented above in the future (say, in 5 years) to retain relevancy with respect to the actual pest and pathogen invasions and climate-related abiotic stressors.

For the sake of efficiency (there are 95 taxa with a relative abundance of <0.01%—Table 2), the discussion was limited to the most common taxa and issues relevant to the study site. There are potentially many further issues related to less common taxa. Nonetheless, even the scientific evidence on the resilience of abundant taxa in the context of roadside tree stands cannot be considered comprehensive and complete. Much of the site-specific information available for particular taxa has been obtained in other tree settings or other parts of the world, which exacerbates their interpretation of the study site. Collection of additional data on roadside tree communities such as age and health status of the trees, panel data on tree populations, regional or local evaluations of tree populations, and further research providing contextual information and guidance on particular species' performance at specific sites remains challenging but is highly recommended as such data are necessary for drawing more specific conclusions and more detailed guidance on taxa selection for the roadside environment. Furthermore, long-term drought experiments are much needed as they are almost non-existing in the literature [46] and are of crucial importance to building expertise for long-term sustainable tree planting [39].

4. Conclusions

The study fills the knowledge gap on the sustainable management of roadside tree populations and focuses on a large-scale pilot site—nine NUTS3 regions in the Czech Republic. The objectives of the study are: (a) to analyze the species composition of roadside tree communities across the country; and to discuss the implications of (b) whether the patterns in newly planted trees favor the sustainability of tree management; and (c) how resilient the roadside tree populations appear with respect to the risks posed by the abiotic environment and emerging pests and diseases.

Focusing specifically on out-of-forest tree species distribution, we show that as much as 75% of the total roadside plantings along second-class and first-class roads are represented by only seven main tree genera of deciduous trees (*Acer*, *Fraxinus*, *Tilia*, *Malus*, *Betula*, *Populus,* and *Quercus*). Across most studied regions, the distribution is similar, and the trends in the selection of new roadside plantings more or less match the original tree species abundance in the region.

The results suggest that both the original composition of trees and the new plantings are largely suitable for the extreme characteristics of tree stands along the roads. Mostly native and relatively resilient tree species are planted, and the effort not to let the invasive trees outgrow into the mature stage is apparent (nonetheless, there are no data available in our study to evaluate the potential invasions through roadside shrub layer). Several existing or emerging issues affecting the sustainability of tree management have been identified. Most importantly, we recommend taking much more into account the susceptibility of some tree species to newly emerging and quickly spreading pests and diseases (*Fraxinus excelsior*) and to saline environments and drought (*Tilia cordata*).

We hope that the results of this study will facilitate the sustainable management of roadside tree populations. For this use, the study was designed as a benchmark for future quick inventories in the pilot area, with the aim to enhance the monitoring of long-term trends in tree species composition. Collection of more detailed data on particular trees in a similar broad extent would be more than welcome, but in practice, it remains challenging.

Our results represent an interesting input into prospective future quick scans of the potential effects (cost or damage estimates) of pests or diseases newly emerging in the future. They also enable us to assess roadside tree plantings as an important part of climate change adaptation measures. Last but not least important direction for the use of our results is the perspective of ecosystem service research. The newly emerging analyses of particular ecosystem services provided by trees in the Czech Republic [47–49] have focused solely on urban or forest environments due to better data availability. Not even the foreign research on ecosystem services has brought any calculations of societal benefits of roadside trees yet. This study may hopefully become the first step to complement the state-of-the-art of knowledge on this topic, which is definitely of no less research interest than the assessment of the trees found in other landscape settings.

Author Contributions: Conceptualization, A.S. and K.M.; methodology, A.S. and K.M.; software, K.M.; validation, A.S., K.M. and J.K.; formal analysis, K.M. and A.S.; investigation, K.M. and A.S.; resources, K.M., J.K. and A.S.; data curation, A.S.; writing—original draft preparation, A.S. and K.M.; writing—review and editing, K.M., A.S. and J.K.; visualization, K.M.; supervision, J.K.; project administration, K.M.; funding acquisition, K.M., J.K. and A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Technology Agency of the Czech Republic, grant number TL01000020 "Authentication of computation of the social value of woody plants growing out of forest for the purpose of calculation of the extent of compensation measures for felling". The support is gratefully acknowledged.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are available upon request. The location of all trees in the data sample is publicly available at www.checktrees.com/map (accessed on 19 April 2022).

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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