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Phytoseiid Mites: Trees, Ecology and Conservation

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Abstract: The highly variable 'leafscapes' of plants across the world represent billions of square metres of mite habitat. The phytoseiid mites (Acari: Phytoseiidae), an extremely species-rich group of mostly generalist predators, are providers of ecosystem services for humanity worth many hundreds of millions of dollars annually by helping suppress phytophagous mites and insects in forests, agro-ecosystems, shade-houses and home gardens. In this study, the phytoseiid mite assemblages on the leaves of four species of common tree species, namely oak (*Quercus cerris* var. *cerris*), poplar (*Populus deltoides*, *P. nigra*) and walnut (*Juglans regia*), were compared. The three data sets used were generated in three independent seasonal studies in Samsun Province, Türkiye, between 2018 and 2022. In total, mite species in 18 families, including 15 families on walnut, were recorded. Nineteen phytoseiid species in 13 genera, *Amblydromalus*, *Amblyseius*, *Euseius*, *Kampimodromus*, *Neoseiulella*, *Neoseiulus*, *Paraseiulus*, *Phytoseius*, *Transeius*, *Typhlodromina*, *Typhlodromips*, *Typhlodromus* and *Typhloseiulus*, were collected. Only *Eusieus amissibilis* was collected from all three tree genera, whereas 14 species were collected from only one tree genus. Shannon diversity and Jaccard similarity indexes were calculated for mite families and phytoseiid genera and species. Potential reasons for the observed differences in the phytoseiid assemblages on the different host trees are explored in depth. In the 'big picture', global biodiversity, likely including many undescribed phytoseiid species, is threatened by widespread habitat degradation and destruction, especially in the tropics, and accelerating climate change, and rapidly stopping them is imperative.

Keywords: competitive exclusion; domatia; IPM; phylloplane; symbiosis; tritrophic

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1. Introduction

1.1. Mites—Diversity and Ecology

The great majority of species across the world are inconspicuous, tropical invertebrates such as insects, crustaceans, mites and nematodes [1,2]. Mites (Acari: Parasitiformes, Acariformes), which represent ~20% of all arthropods, are an extremely large and extraordinarily diverse group [3–5]. Conservative estimates of the total number of mite species worldwide range from 500,000 to 1,500,000 [4–7], with most species understood to be tropical [4,7–15].

Mites, which have an enormous range of morphologies, ecologies and behaviours, inhabit terrestrial, freshwater and marine ecosystems, habitats and microhabitats from the ocean depths to high mountains and as far as the polar regions [3,4,7,16]. Mite species are phytophagous, parasitic, predatory or omnivorous, and consume algae, decaying organic

material, detritus, fungi, fungal spores, lichens, microbes, mosses, nectar and pollen [16]. Honeydew is also consumed [4,17].

In the 'big picture', mites may represent 10% of all eucaryotic species and are vital contributors to both global ecological functioning and ecosystem services.

1.2. Plants as Mite Habitat

Globally, there are more than 370,000 described plant species [18] which provide billions of square metres of leaf area that represent great opportunity but also diverse threats to the establishment, survival and reproduction of mites. More specifically, plant foliage provides a spectrum of feeding and shelter opportunities but mites living there must contend with continually changing abiotic conditions that include exposure to rain droplet impacts and runoff, UV light, wind, leaf movement, humidity and temperature variations, dust and industrial pollutants, and variable biotic conditions, including leaf morphology, leaf fall in deciduous trees, toxic plant metabolites in plant tissues and prey, predation and competition.

Around 2000 new plant species are described each year [18], and there are an estimated 450,000 [19] or 500,000 [20] plant species globally. One of the most obvious and intriguing aspects of nature is how much the size, shape and other morphological features of leaves vary across the vast spectrum of plant species, and yet still perform their primary function, photosynthesis.

Even a single leaf blade (lamina, phylloplane) can be considered a three-dimensional habitat composed of potential microhabitats exploitable by a wide spectrum of mite taxa. In addition to their raised leaf veins, many species of woody plants produce tufts of hairs and more elaborate pits, pouches, pockets and domes in their vein axils, known as domatia [4,21–23].

Leaf domatia house fungivorous and predaceous mites that prey on plant enemies, which is an example of plant-mite mutualism [21]. Fossil data from the families Elaeocarpaceae and Lauraceae indicate that mite–plant associations mediated by domatia may have been widespread in southern Australia 40 million years ago [24].

Leaf surface structures affect both mite assemblages and abundances, and predator–prey interactions, and are fundamental to the understanding of the relationship between mites and plants [22,23,25–30]. As an example, the differences in leaf mite populations between adjacent trees with differences in pubescence (hairiness) can be substantial. Pubescent leaves in tropical rainforests in Australia typically averaged three times as many species and five times as many individual mites as smooth (glabrous) leaves at the same site [4].

1.3. Phytoseiid Mites

The phytoseiid mites (Mesostigmata: Phytoseiidae), which belong to one of three subfamilies, namely Amblyseiinae Muma, Phytoseiinae Berlese and Typhlodrominae Chant and McMurtry [31], have undergone a spectacular evolutionary radiation on higher plants. The phytoseiids, most of which are generalist predators [30], are characteristically small, in the range of 200–600 μm in length. In the foliage-inhabiting species, many of the body and leg setae found in their soil-inhabiting relatives have been suppressed [4].

The diversity of phytoseiid mites likely increases from temperate to tropical regions; however, the temperate region phytoseiid faunas are currently better known than the subtropical and tropical faunas [4,9,11–13,27,28,32–40].

Most of the ~2560 known valid phytoseiid species have been described in recent times [9,32,33,36,37,40–47] because of their importance as biological control agents in agriculture [43,44,48–59]. Aerial dispersal is an important contributor to the dispersal of phytoseiid mites [60], which are important control agents of spider mites, thrips and whiteflies [61].

In Türkiye, ~140 phytoseiid species have been recorded from 24 genera in the three subfamilies [14,62–79]. The reporting of ~5.5% of the world's known phytoseiid species

from Türkiye is not surprising because it is rich in biodiversity due to wide variations in factors such as climate, elevation and soil type, and its phytoseiid fauna is well studied, especially in comparison with that of most tropical regions.

1.4. The Present Study

To better understand the biogeography and ecology of the phytoseiid mites, this study compared the species collected from four common tree species in the genera, *Juglans*, *Populus* and *Quercus*, in Samsun Province, Türkiye. This study also compared the mite families collected from the same host plants.

2. Materials and Methods

2.1. Data Sources for the Study

This study used data compiled from three separate surveys of mites inhabiting the foliage of walnut (*Juglans regia* L.), oak (*Quercus cerris* L. var. *cerris*) and poplar (*Populus deltoides* Marsh, *Populus nigra* L.) trees in Samsun Province, Türkiye, conducted during the period 2018 to 2022 [69–78].

2.2. Location, Biogeography and Climate of Samsun Province, Türkiye

Samsun Province is in the central–eastern Black Sea region of northern Türkiye. It covers an area of 9579 sq km [80], has a long interface with the Black Sea, contains the extensive deltas of the Kizilirmak and Yesilirmak (Red and Green Rivers, respectively), and extends inland over a forested coastal mountain range and into the Anatolian plains.

The province experiences a range of climates; Samsun city, the administrative centre, which is on the coastline, has a hot, Mediterranean/dry summer, subtropical climate (Koppen-Geiger classification: Csa). According to the Holdridge life zones system of bioclimatic classification, Samsun is in or near the cool, temperate, moist forest biome [81], whereas the town of Vezirkopru, which is inland of the coastal range, has a marine west coast, warm summer climate (Classification: Cfb) [82]. Samsun city and Vezirkopru town are about 75 km distant in a direct line.

2.3. Host Tree Species Investigated for Phytoseiids

The walnut tree, *J. regia*, has long been cultivated in Türkiye as individual trees, small plots or in plantations. Poplar (*P. deltoides*, *P. nigra*), which is widely grown as a specimen, windbreak and plantation tree, is used for fruit boxes, pallets, light construction work and firewood. There are now many small, short-rotation poplar plantations on the alluvial Carsamba Plains of the Yesilirmak (Green River), 30 km to the east of Samsun city, that have greatly boosted production. The oak trees (*Q. cerris* var. *cerris*) surveyed were in several remnant and regenerating native forest areas on the approximately 600 hectare campus of Ondokuz Mayis University which is located about 15 km west of Samsun city centre and runs from sea level to low hills.

2.4. Identification of Phytoseiid Species

The phytoseiids from the two poplars and oak were identified by the sixth author (I.D.), and those from the walnut were identified by the seventh author (M.-S.T.), using generic classifications [43].

2.5. Diversity Assessments

2.5.1. Shannon Diversity Index

The Shannon diversity index [83] was used to estimate and compare the diversities of the mite families, and phytoseiid genera and species, from three genera of trees, as described in Section 2.3.

2.5.2. Jaccard Similarity Index

The Jaccard index [84] was used to estimate and compare the similarities of the mite families, and phytoseiid genera and species, from trees in three genera (see Section 2.3).

3. Results

3.1. Mite Families

Phytoseiid mites (Phytoseiidae) living on the foliage of trees are only one of the many mite families exploiting that environment. From Samsun Province, Türkiye, 40 species from 15 mite families, namely Anystidae, Cheyletidae, Cunaxidae, Eriophyidae, Glycyphagidae, Iolinidae, Oribatulidae, Phytoseiidae, Stigmaeidae, Tarsonemidae, Tenuipalpidae, Tetranychidae, Triophtydeidae, Tydeidae and Winterschmidtiidae, were reported from the walnut tree, *Juglans regia* [70]; 28 species in nine families, Acaridae, Eriophyidae, Iolinidae, Phytoseiidae, Tarsonemidae, Tenuipalpidae, Tetranychidae, Triophtydeidae and Tydeidae, were collected from either or both of the poplar tree species, *Populus deltoides* and *P. nigra* [76]; and 21 species in eleven families, Diptilomiopidae, Eriophyidae, Eupodidae, Iolinidae, Phytoseiidae, Tarsonemidae, Tenuipalpidae, Tetranychidae, Triophtydeidae, Tydeidae and Winterschmidtiidae, were collected from the oak tree, *Quercus cerris* var. *cerris* [77]. Eight of the 18 mite families were found on all three genera of trees, and six mite families were only collected from *J. regia* (Figure 1).

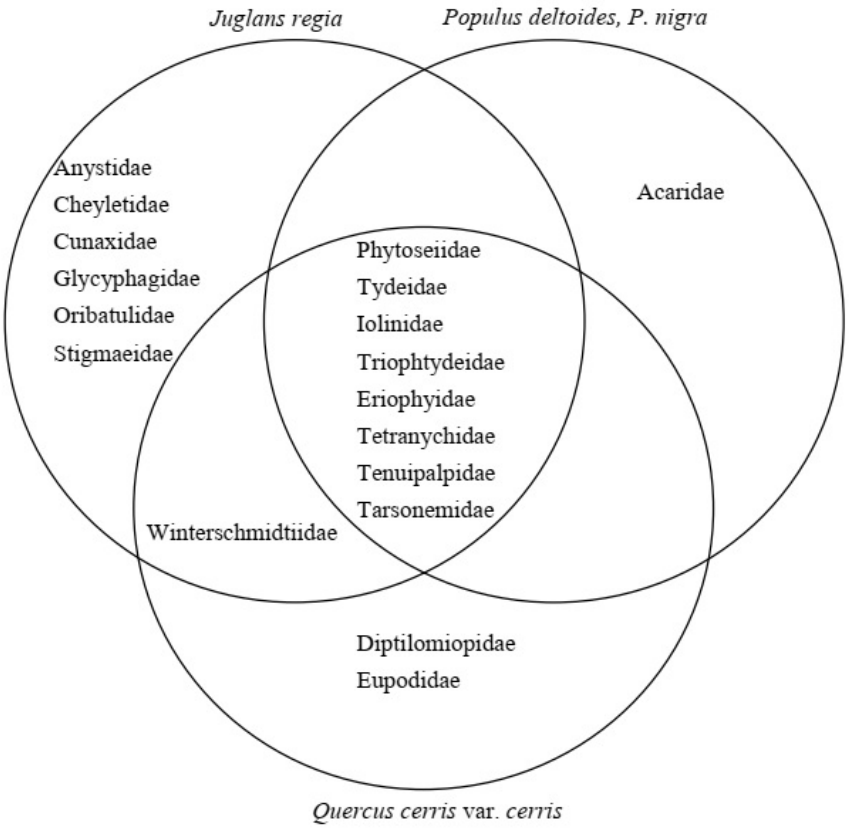


Figure 1. Mite families collected from walnut (*Juglans regia*), poplar (*Populus deltoides* and/or *P. nigra*) and oak (*Quercus cerris* var. *cerris*) trees in Samsun Province, Türkiye, between 2018 and 2022.

3.2. Phytoseiid Genera and Species

With respect to the specific subject of this study, namely the phytoseiid mites, a total of 19 species in 13 genera and three subfamilies were collected from *J. regia*, *P. deltoides*, *P. nigra* and *Q. cerris* var. *cerris*, in Samsun Province, Türkiye, in three separate surveys, between 2018 and 2022 (Table 1).

Table 1. Phytoseiid mite species collected from walnut, poplar and oak trees in Samsun Province, Türkiye between 2018 and 2022.

Phytoseiid Species	Plant Species		
	Walnut (*Juglans regia*)	**Poplar (*Populus deltoides*, *P. nigra*)**	**Oak (*Quercus cerris* var. *cerris*)**
Amblydromalus limonicus	_	X	_
Amblyseius andersoni	X	X	_
Amblyseius bryophilus	_	X	_
Euseius finlandicus	X		X
Euseius amissibilis	X	X	X
Euseius stipulatus	X	X	_
Kampimodromus aberrans	X	_	_
Kampimodromus langei	_	_	X
Neoseiulella tiliarum	X	_	_
Neoseiulus fauveli	_	X	_
Paraseiulus triporus		X	_
Phytoseius finitimus	X	_	X
Transeius wainsteini	_	X	_
Typhlodromina conspicua	_	X	_
Typhlodromips sessor		X	_
Typhlodromus (*Anthoseius*) *intercalaris*	_	_	X
Typhlodromus (*Anthoseius*) *rapidus*	X	_	_
Typhlodromus (*Anthoseius*) sp.	X	_	_
Typhloseiulus peculiaris	_	_	X

X = present.

A total of nine phytoseiid species in six genera were collected from the walnut, *J. regia*. They were *Euseius amissibilis* Meshkov (=*E. gallicus* Kreiter & Tixier), *Euseius finlandicus* (Oudemans), *Euseius stipulatus* (Athias-Henriot), *Kampimodromus aberrans* (Oudemans), *Neoseiulella tiliarum* (Oudemans), *Phytoseius finitimus* Ribaga, *Typhlodromus* (*Anthoseius*) *rapidus* (Wainstein and Arutunjan), *Amblyseius* (*andersoni*?) sp. and *Typhlodromus* (*Anthoseius*) sp. Phytoseiids were collected from 268 (24.8%) of the 1080 walnut leaves collected in total, and their mean density across all leaves, including both the upper and lower surfaces, was 0.18 individuals per 8 cm^2. *Euseius finlandicus* was the most abundant species (45.5%), followed by *Phytoseius finitimus* (24.6%) and *E. amissibilis* (11.7%) [70,71].

Ten phytoseiid species in eight genera were collected from the poplars, *P. deltoides* and *P. nigra*, combined. They were *Amblydromalus limonicus* (Garman & McGregor) (*P. deltoides* and *P. nigra*), *Amblyseius andersoni* (Chant) (*P. deltoides*), *Amblyseius bryophilus* Karg, (*P. deltoides*), *E. amissibilis* (*P. deltoides* and *P. nigra*), *E. stipulatus* (*P. deltoides* and *P. nigra*), *Neoseiulus fauveli* (Athias-Henriot) (*P. nigra*), *Paraseiulus triporus* (Chant & Yoshida-Shaul) (*P. deltoides*), *Transeius wainsteini* (Gomelauri) (*P. deltoides* and *P. nigra*), *Typlodromina conspicua* (*P. deltoides* and *P. nigra*) and *Typhlodromips sessor* (De Leon) (*P. deltoides*). The mean phytoseiid density was 0.014 individuals per 8 cm^2 across all leaves, including both the upper and lower surfaces. *Amblydromalus limonicus* (24%) and *E. amissibilis* (24%) were the most common species, followed by *E. stipulatus* (20%) [69,72,73,76].

In addition, six phytoseiid species in five genera were reported from the oak, *Quercus cerris* var. *cerris*, namely *E. amissibilis*, *E. finlandicus*, *Kampimodromus langei* Wainstein and Arutunjan, *P. finitimus*, *Typhloseiulus peculiaris* (Kolodochka) and *Typhlodromus intercalaris*

Livshitz & Kuznetsov. Among them, *T. intercalaris* (51.4%) was the most abundant species, followed by *K. langei* (38.7%) and *T. peculiaris* (7.1%). Phytoseiids were collected from 89 (9.4%) of the 950 oak leaves collected in total and their mean density was 0.13 individuals per 8 cm^2 across all leaves, including both the upper and lower surfaces [74,75,77,78].

Of the phytoseiid species reported from these three surveys, only five of the 13 genera were collected from two or more host tree genera, including one genus, *Euseius,* that was on all three host tree genera (Figure 2). Only four phytoseiid species were collected from two or more tree genera, and they included, *E. amissibilis*, which was found on all three tree genera. In contrast, fourteen phytoseiid species were found on only one host plant genus. The genera, *Euseius* and *Typhlodromus*, were both represented by three species (Table 1).

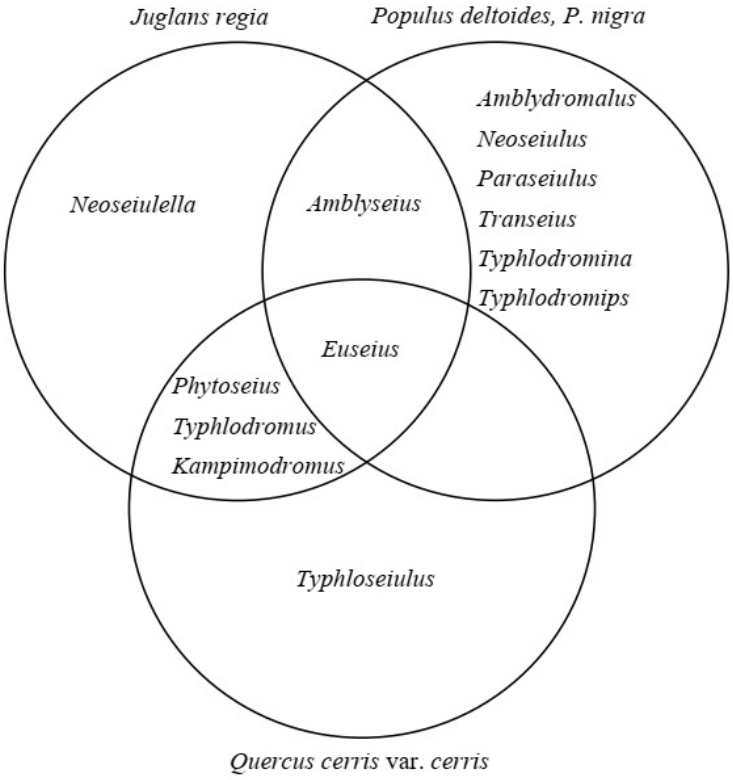


Figure 2. Genera of the mite family Phytoseiidae collected from walnut (*Juglans regia*), poplar (*Populus deltoides* and/or *P. nigra*) and oak (*Quercus cerris* var. *cerris* in Samsun Province, Türkiye, between 2018 and 2022.

3.3. Diversity Assessments

3.3.1. Shannon Diversity Index Comparisons

In the present study, the Shannon diversity index was used to compare the differences in diversities among the mite families, and the phytoseiid genera and species, collected from the three tree genera described in Section 2.3. *Quercus cerris* var. *cerris*, *P. deltoides* and *P. nigra*, and *P. deltoides* and *P. nigra*, had the highest Shannon indexes of 1.81, 1.53 and 1.87 for mite families, phytoseiid genera and phytoseiid species, respectively. *Quercus cerris* var. *cerris*, *P. deltoides* and *P. nigra*, and *P. deltoides* and *P. nigra*, also had the highest evenness values of 0.76, 0.74 and 0.81 for mite families, phytoseiid genera and species, respectively (Table 2).

Table 2. Shannon diversity index (H) and evenness (E) values for mite families and phytoseiid mites on the leaves of four tree species in three genera in Samsun Province, Türkiye.

Mite Taxa	Shannon Index	Walnut (*Juglans regia*)	Poplar (*Populus deltoides* and *P. nigra*)	Oak (*Quercus cerris* var. *cerris*)
Families	H	1.60	1.63	1.81
	E	0.59	0.74	0.76
Genera (phytoseiid)	H	1.15	1.53	1.02
	E	0.64	0.74	0.63
Species (phytoseiid)	H	1.54	1.87	1.02
	E	0.70	0.81	0.57

3.3.2. Jaccard Similarity Index Comparisons

In this study, the Jaccard similarity index was used to compare similarities at the mite family, phytoseiid genus and phytoseiid species levels for the combinations of walnut–poplar, walnut–oak and poplar–oak, which ranged from 0.50 to 0.67, 0.08 to 0.57, and 0.07 to 0.25, respectively (Table 3).

Table 3. Jaccard similarity index values for mite families and phytoseiid mites on the leaves of four tree species in three genera in Samsun Province, Türkiye.

Mite Taxa	*J. regia*/*Populus* spp.	*J. regia*/*Q. cerris* var. *cerris*	*Populus* spp./*Q. cerris* var. *cerris*
Families	0.50	0.53	0.67
Genera (phytoseiid)	0.17	0.57	0.08
Species (phytoseiid)	0.19	0.25	0.07

4. Discussion

4.1. Mite Habitat and Microhabitat on the Foliage of Trees

The surfaces of the leaves of plants worldwide collectively provide billions of square metres of potential mite habitat, including both the strictly predatory and omnivorous phytoseiid mites, but it can be a harsh environment due to major temperature, light, humidity and wind fluctuations; leaf vibration and friction of leaf on leaf; dust and industrial pollutant particles; droplet impact and water flow during rainfall events; UV radiation; and the usual biotic phenomena such as competition, predation and pathogens. Leaf fall is also a consideration for species associated with trees that lose their leaves in autumn in temperate regions or during dry periods in tropical regions.

Leaf surface structures alter mite abundances, influence predator–prey interactions, and are central to an understanding of the relationship between mites and plants [23,28,85]. Refuges are scarce, especially on the upper surface of leaves, which are generally much less morphologically diverse than lower leaf surfaces. The most obvious refuges are the sides of the veins and the vein angles, which are generally more pronounced on the lower leaf surface, but the most distinctive refuges are the various forms of 'acarodomatia' or 'mite houses', generally referred to as domatia [4,86]. Their presence or absence, their type, their location and their abundance are specific to the host plant species and can even vary across the distribution of a particular plant species. Domatia are important to phytoseiids as protected sites for oviposition and moulting [4,23,29,30,87,88]. In addition, pubescent leaves have a consistent, positive effect on phytoseiid densities [23]. Leaf buds and newly emerging leaves on shoots also provide feeding and sheltering sites.

The extreme smallness of most mite species, and the relatively large size of leaves and morphological features that project above the leaf surface subdivide the individual leaf into an aggregation of microhabitats. As one example, mite predators on leaves can

include cheyletids (Cheyletidae), which are ambush predators that often wait for prey at the base of a leaf petiole; stigmaeids (Stigmaeidae), which generally search the leaf surface for non-moving prey like eggs and moulting individuals; cunaxids (Cunaxidae; Cunaxinae), which are ambush predators on the leaf surface; and phytoseiids, which rapidly search the leaf surface [4].

4.2. Comparison of Diversities of Mite Families, and Phytoseiid Genera and Species, Collected from Walnut, Poplar and Oak Trees

In this study, mite species belonging to 18 families, including Phytoseiidae, are reported from four tree species in three genera (Figure 1). In total, 19 phytoseiid species (Table 1) in 13 genera (Figure 2) are reported.

The Shannon diversity index estimates diversity within a community. It rises with the number of species and their evenness. For 'real-world' ecological data, Shannon diversity index values usually range from 1.5 to 3.5 [83].

In the current study, the Shannon diversity indexes at the mite family level ranged from 1.6 for *J. regia* to 1.8 for *Q. cerris* var *cerris*, at the phytoseiid genus level ranged from 1.0 for *Q. cerris* var *cerris* to 1.5 for *P. deltoides* and *P. nigra*, and at the phytoseiid species level ranged from 1.0 for *Q. cerris* var *cerris* to 1.9 for *P. deltoides* and *P. nigra* (Table 2). These values are low because mites, including the phytoseiid mites, constitute only a small proportion of the biodiversity associated with the host trees. Separately, evenness values (range: 0 to 1) at the family level ranged from 0.59 for *J. regia* to 0.76 for *Q. cerris* var *cerris*, at the phytoseiid genus level ranged from 0.63 for *Q. cerris* var *cerris* to 0.74 for *P. deltoides* and *P. nigra*, and at the phytoseiid species level ranged from 0.57 for *Q. cerris* var *cerris* to 0.81 for *P. deltoides* and *P. nigra* (Table 2).

The Jaccard similarity index is used to compare the similarity of two sets of data. Values can range from zero to one, with one indicating identical data sets [84].

In the present study, the Jaccard similarity indexes at the mite family, phytoseiid genus and phytoseiid species levels for the combinations, walnut–poplar, walnut–oak and poplar–oak, ranged from 0.50 to 0.67, 0.08 to 0.57 and 0.07 to 0.25, respectively (Table 3). This meant that similarity at the mite family level was consistently much higher than at the phytoseiid genus and phytoseiid species levels. That situation is exemplified by a substantial degree of similarity at the mite family level (0.67) for the poplar–oak combination, whereas the phytoseiid genera and species were highly dissimilar at 0.08 and 0.07, respectively (Table 3).

4.3. Factors Determining the Phytoseiid Species and Their Densities on Walnut, Poplar and Oak Trees

In the present study, the phytoseiid species and their occurrences on *J. regia* (walnut), *P. deltoides* and *P. nigra* (poplar), and *Q. cerris* var. *cerris* (oak), would have been influenced by the following phenomena: (1) physical environment (latitude, longitude, elevation, site aspect, degree of site exposure, direction of prevailing winds, climate, season, weather, soil type, soil nutritional status and local and regional vegetation); (2) leaf morphology, biochemistry and physiology of the host tree species, and ages of individual host trees and their leaves; and (3) interactions with the other groups of species (predators, prey, competitors, neutral species) sharing the foliage (see also Section 1.2). As one example, intraguild predation [52,89] is likely to have been a factor in determining the presence/absence of a particular phytoseiid species and the proportions of each species. Pesticide use would also likely have influenced the presence or absence of individual phytoseiid species in most walnut plantations but generally not in small plots and on individual trees.

This comparative study determined that the density of phytoseiids was 13 and 9 times greater on the walnut and oak leaves, respectively, than on the poplar leaves. Separately, the most common phytoseiid species were different on the leaves of walnut, oak and poplars [70,76,77].

In summary, in this study, the interactions of all the abiotic and biotic factors mentioned above would have dictated which phytoseiids were present on the leaves of a particular tree genus or species, or on any individual tree, at a particular time. That said,

the leaf morphologies or 'leafscapes' of the different tree species would have been critical determinants of the phytoseiid species present.

4.4. Lifestyles of the Phytoseiids Reported in This Study

The lifestyles/feeding habits of phytoseiid mites are the best known of any group of foliage-inhabiting mites. Most appear to be generalist, opportunistic predators of the various life-stages of mites and insects but are capable of subsisting on non-prey foods. The food resources of leaf-inhabiting phytoseiids include the eggs, nymphs and adults of omnivorous, parasitic, phytophagous and predatory insects and mites, and pollen, nectar and fungal spores. Also, some phytoseiids feed on their conspecifics, congeners and other groups of phytoseiids [3,4,16,52,90–92].

There are four types of phytoseiid mites, depending on their feeding strategies: (I) specialised mite predators (three subtypes), (II) selective predators of tetranychid mites, (III) generalist predators (five subtypes), and (IV) pollen-feeding generalist predators. There is also a possible fifth lifestyle, namely "the ability to pierce leaf cells" [92].

4.5. Phytoseiid Mites on Walnut, Poplar and Oak Trees across Turkish and International Studies

4.5.1. Walnut Trees

From walnut trees, *J. regia*, in Samsun Province, Türkiye, 40 mite species in 15 families, Anystidae, Cheyletidae, Cunaxidae, Glycyphagidae, Oribatulidae, Stigmaeidae, Phytoseiidae, Tydeidae, Iolinidae, Triophtydeidae, Eriophyidae, Tetranychidae, Tenuipalpidae, Tarsonemidae and Winterschmidtiidae, were reported [70], with both counts considerably higher than for the poplar and oak trees.

Nine phytoseiid species from six genera that included *Euseius* (three species) and *Typhlodromus* (two species), with the remaining four genera, *Amblyseius*, *Kampimodromus*, *Neoseiulella* and *Phytoseius*, each represented by one species, were documented [70] (Table 1). *Euseius finlandicus* was the most abundant species (45.5%), followed by *P. finitimus* (24.6%) and *E. amissibilis* (11.7%), which meant that the two and three most abundant species represented 70% and 82%, respectively, of all phytoseiid species collected from *J. regia* [70].

The ecologies of the nine phytoseiid species reported vary considerably, as follow. *Amblyseius andersoni* (Type III) prefers spider mites to eriophyoid mites as prey [93]. *Euseius* species are pollen-feeding, Type IV generalist predators [90,92]. The diet of some *Euseius* species can be very broad and includes prey, pollen, honeydew and plant exudates [17]. *Euseius finlandicus*, a classical omnivore, can feed on tetranychid, eriophyid, tyroglyphid and tarsonemid mites, pollen, fungal spores and hyphae, eggs and larvae of insects, honeydew and plant liquids [50,94], and *E. stipulatus* is a pollen-feeding, generalist predator that can feed on tetranychid mites [90,92].

Kampimodromus aberrans, a generalist predator (Type III), also feeds on pollen and fluids that it extracts from leaves [90]). It feeds on tetranychid mites [51,95] and eriophyoid mites [96,97]. *Neoseiulella tiliarum*, also a generalist predator (type III), feeds on tetranychid and eriophyoid mites [98,99], and *P. finitimus* is another generalist predator (type III) that feeds on eriophyid and tetranychid mites, other small arthropods and pollen [56,98].

Typhlodromus rapidus is, as are all *Typhlodromus* species, a type III generalist predator [90]). In a specific case from an agricultural environment, larger populations of *Typhlodromus pyri* Scheuten on apple plants with pubescent leaves were due, in part, to the increased capture and retention of pollen and fungal spores that serve as alternative foods [100].

There have been other reports of phytoseiids on walnut trees from Türkiye and abroad. In eastern Türkiye, *E. finlandicus*, *K. aberrans*, *Paraseiulus soleiger* (Ribaga) and *Typhlodromus* (*Anthoseius*) *bagdasarjani* Wainstein and Arutunjan were reported from walnut plantations in the Van Lake region. *Euseius finlandicus* was abundant, especially in unsprayed orchards, and was seen feeding on phytophagous mites [101,102]. *Euseius finlandicus* was reported feeding on eriophyoid mites on walnut trees in Ankara Province, Türkiye [103]. This species was also reported from walnut trees in Tekirdağ Province in north-western Türkiye [104].

Also from Western Asia, *E. finlandicus* was found in *Amphitetranychus viennensis* (Zacher) colonies on walnut leaves in Iran [105]. Again from Iran, *E. amissibilis, E. finlandicus* and *Euseius* sp. were observed feeding on the eriophyid mite, *Aceria erinea* (Nalepa), in walnut plantations [106].

In a North American study, 11 phytoseiid species were collected from walnut orchards in nine counties in California, U.S.A. The predominant genera in the Central Valley were type III lifestyle *Amblyseius* species (58.0%) and type IV lifestyle *Euseius* species (28.7%). In contrast, walnut trees growing in the Sacramento Valley had a much higher percentage of type II *Galendromus occidentalis* (26.1%) and type III *Typhlodromus* species (18.1%), in addition to *Euseius* species (49.5%), and very low numbers of *Amblyseius* (1.7%) species [57].

There was a decline in the species richness of phytoseiids between the northern and southern walnut growing regions of the Central Valley of California, U.S.A. [59] that was in contrast with a broader pattern of increased phytoseiid species richness from 80° N to 20° N [36]. Rather than a latitudinal effect, the north-south decline in phytoseiid species' richness in walnut growing regions [59] may have been a consequence of orchard management practices, or crop diversity in the surrounding landscape, or a combination of them [107]. A north–south gradient in the increasing use of broad-spectrum pesticides in walnut orchards could also have been a contributing factor [59].

From Europe, eight phytoseiid species in six genera, *Amblyseius*, *Euseius*, *Neoseiulella*, *Paraseiulus*, *Phytoseius* and Typhlodromus, were reported from abandoned and uncultivated walnut trees in the Czech Republic. The most abundant species was *E. finlandicus*, followed by *N. aceri*. The presence of only one phytoseiid species per walnut leaflet was the most common observation, but the co-occurrence of two species, mostly *E. finlandicus* with *N. aceri*, was also noted [108].

The difference in phytoseiid assemblages between California and Europe may be a consequence of web-producing *Tetranychus* species being the dominant prey in California, whereas non-web-producing, *Panonychus ulmi* (Koch), and eriophyid mites, are the dominant prey in Europe. The mean proportional abundance of the dominant phytoseiid lifestyles and species in California were also affected by walnut growing region and cultivar [59].

Two-thirds (68%) of all the phytoseiids collected from leaves of *J. regia* in Samsun Province, Türkiye were on the lower surface [70]. In the bigger picture, many mite taxa commonly prefer to live on the lower leaf surfaces of wild vegetation [109]. These were unsurprising findings given that living in the 'shade' on the underside of the leaf would reduce exposure to environmental stressors such as extremes of humidity, temperature, rain, UV light, wind, dust and industrial pollutants. Life on the lower leaf surface also provides access to more shelter, given the presence of a much more three-dimensional 'leafscape' due to the presence of raised veins, vein angles, pubescence, domatia and stomata. Generally, there would also be increased access to food resources and shelter from predators. One drawback of living on the underside of leaves would appear to be living 'upside down', but that challenge has apparently been overcome!

4.5.2. Poplar Trees

From Samsun Province, Türkiye, a total of 28 mite species in 17 genera in nine families (Acaridae, Eriophyidae, Iolinidae, Phytoseiidae, Tarsonemidae, Tenuipalpidae, Tetranychidae, Triophtydeidae and Tydeidae), including ten phytoseiid species in eight genera, were collected from the foliage of two poplar species, *P. deltoides* and/or *P. nigra*. Among the phytoseiids, *E. amissibilis* (24%) and *A. limonicus* (24%) were the most common species, followed by *E. stipulatus* (20%). Together, they contributed 68% of all the phytoseiids collected [76].

In stark contrast, from a forest near Vrchoviny in the Czech Republic, no phytoseiid mites were collected from a different species, *Populus tremula* L., which has glabrous leaves and non-raised veins. This was despite most leaves being inhabited by tydeid, eriophyid and acarid mites, which are suitable prey for various phytoseiid mites. Thus,

food availability is understood to have not limited the occurrence of phytoseiids on the leaves of *P. tremula*. Instead, the lack of refuges, e.g., trichomes on leaf laminae, raised veins with hairs and domatia, may explain the absence of phytoseiids [110].

4.5.3. Oak Trees

Twenty-one species in 11 families, Diptilomiopidae, Eriophyidae, Eupodidae, Iolinidae, Phytoseiidae, Tarsonemidae, Tenuipalpidae, Tetranychidae, Triophtydeidae, Tydeidae and Winterschmidtiidae, were collected from the leaves of the oak tree, *Q. cerris* var. *cerris*, in remnant forests on the campus of Ondokuz Mayis University in Samsun Province, Türkiye [77] (Figure 1). The 21 species included six phytoseiid species in five genera (Table 1). *Typhlodromus* (*A.*) *intercalaris* (51.4%) was the most abundant species, followed by *K. langei* (38.7%) and *T. peculiaris* (7.1%). That these two most abundant species contributed 90.1% of all phytoseiids suggests that the prevailing combination of biotic and abiotic conditions strongly favoured these two species.

From various sites across Serbia, a total of nine phytoseiid species, namely *A. andersoni*, *E. finlandicus*, *K. aberrans*, *Neoseiulella aceri* (Collyer), *Typhlodromus* (*A.*) *bakeri* (Garman), *T. intercalaris*, *Typhlodromus* (*A.*) *rhenanus* (Oudemans), *T. peculiaris* and *Typhloseiulus simplex* (Chant) were reported from seven oak species, including *Q. cerris*, from which all nine phytoseiid species were recorded. *Quercus frainetto* Ten. had six species recorded from it and the other five oak species had between one and four species associated with them. *Euseius finlandicus* was reported from all seven oaks species and was present in 60% of the 78 leaf samples (100 leaves per sample) collected [111].

In a different European study, five phytoseiid species, *K. aberrans*, *T. peculiaris*, *E. finlandicus*, *T. pyri* and *P. triporus*, were collected from the leaves of *Q. cerris* in an urban park in Prague, Czech Republic. *Kampimodromus aberrans* and *T. peculiaris* were the dominant species, constituting 88.5% of all the collected phytoseiids, of which *K. aberrans* was by far the most abundant species. Furthermore, it was concluded that the exotic species *Q. cerris* can serve as a host plant and refuge for phytoseiid species in an 'environmentally unfriendly' urban area [112].

4.6. Sampling

4.6.1. Sampling Effort

In the current comparative study, the survey of phytoseiids on poplars in Samsun Province [69,72,73,76] documented the most diverse phytoseiid assemblage of the three surveys compared, indicating that the foliage of some poplars does indeed provide diverse microhabitats and ecological niches for the feeding and reproduction of mites, including phytoseiids. However, it should be remembered that this result was achieved in the context of the survey of two *Populus* species and only one species of both *Juglans* and *Quercus*. Furthermore, the survey of *Q. cerris* var. *cerris* was restricted to the 600 hectare campus of Ondokuz Mayis University in Samsun Province, whereas the poplar and walnut tree surveys were conducted in many different areas of the province.

4.6.2. Sampling Efficiency

An interesting question that arises from these surveys is what proportion of the total number of mite species present were collected. The two poplar, one oak and one walnut species surveyed are large trees; so, most of the foliage sampling was conducted in the lower thirds of the trees' foliage for convenience and safety reasons, although an extendible pruning pole was used on the poplars that allowed for sampling up to seven metres. This meant that the top two thirds of the canopies of the oaks and the walnuts were not sampled, except for some juvenile trees, in any of the surveys. Another question arises as to whether the upper thirds of the different tree species harboured the same mite faunas as their lower and middle thirds, assuming that the abiotic conditions were different.

5. Concluding Remarks

5.1. An Overview of This Study

The foliage of trees represents both opportunities (food, shelter, completion of the reproductive cycle) and threats (environmental extremes, competition, predation, pathogens, toxins) for phytoseiid mites. The presence of 19 phytoseiid species in 13 genera on four tree species in three genera (*Juglans*, *Populus* and *Quercus*) in Samsun Province, Türkiye indicates that the phytoseiids have the ecological resilience to colonise and persist on the stated host trees.

In the context of tritrophic relationships, the phytoseiids suppress the numbers of phytophagous mites and insects and therefore indirectly boost the biomass production of plants. Across the world in natural habitats, planted forests, agricultural landscapes, shadehouses and home gardens, this phenomenon constitutes an extremely valuable ecosystem service likely worth hundreds of millions, and possibly billions of dollars, annually.

In this comparative study, the different suites of phytoseiid species inhabiting the leaves of trees in three genera reflected: (1) the morphological, biochemical and physiological differences between the tree genera and species in terms of their provision of suitable habitat, microhabitat and niches for feeding, shelter, reproduction, and ultimately, persistence; (2) the spectrum of mite and insect prey species, including their nymphal stages and eggs, and other dietary items such as pollen, fungal spores, nectar, leaf exudates and honeydew available; (3) the predators and competitors of phytoseiids present; (4) the competitive abilities of the individual phytoseiid species in the particular leaf environments provided by the three tree genera; and (5) the effects of compounding environmental stresses such as humidity and temperature fluctuations, rainfall disturbance, dust and airborne pollutants, UV light and wind.

The impressive total of phytoseiid genera and species documented in this study on phytoseiid mites on the foliage of walnut, poplar and oak trees in Samsun Province, Türkiye likely also reflects the absence of pesticide use, except for most of the walnut plantations. Another relevant factor is the relative stability of habitat that the host walnut, poplar and oak trees provide because they are long-lived perennials with large expanses of foliar microhabitat, and overwintering opportunities during the deciduous period, e.g., in bark crevices, for both predators, prey and neutral species. More broadly, the results of this comparative study demonstrated that oak forest remnants, poplar plantations and walnut plantations, and even small plots and individual trees, are serving as valuable habitat and refugia for 18 mite families across the ecological spectrum.

5.2. Additional Considerations

5.2.1. Loss of Taxonomic Expertise

The number of specialists in invertebrate taxonomy is falling at the same time as there is an increasingly desperate need to describe as many as possible of the world's enormous number of undescribed species, given the increasing threats to the existence of almost all forms of biodiversity. This situation can be partly compensated for by using molecular techniques to help more quickly and reliably identify the beautiful and fundamentally important unseen biodiversity all around us. However, there is no real substitute for the training of new invertebrate taxonomists and the long-term funding of traditional taxonomic research for their major contribution to biodiversity description, public education, and advice to the farming and health sectors.

5.2.2. Conservation Status of Mite Species, Including Phytoseiids

Most of the attention on global wildlife is focused on plants and vertebrates. However, as important as they are, the number of species in those two groups combined is dwarfed by the numbers of insect and mite species, yet most persons know little about them.

The life and death struggles of the phytoseiid mites and the other mites and insects on leaves are no less intense and dramatic than those of the lions, leopards and wildebeest on the African savannas that are so often shown in television documentaries. A documentary

of life at the microscale of the microfauna on the leaves of trees with a voice over by David Attenborough or another renowned wildlife authority would surely also make compelling viewing and generate more public knowledge of the mites and other small invertebrates of the world and their fundamental importance to global ecology.

Knowing that both the phytoseiid mites collected in the present study and their networks of tritrophic relationships are persisting in a world suffering from enormous, continuing biodiversity loss and rapid climate change due to gross ecological overshoot by humanity gives some reason for hope. However, the rapid termination of habitat destruction, degradation and fragmentation, and fossil fuel use, are essential across the world if humanity is to save a high proportion of the Earth's remaining biodiversity.

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