Forest Ecology and Management

Tree invasions in Italian forests

--Manuscript Draft--

Manuscript Number:	
Article Type:	Full Length Article
Keywords:	invasive alien species; exotic trees, non-native trees; Silviculture; biodiversity; global change
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Abstract:	Many forest tree species have been moved outside their native range to provide goods and services elsewhere, but some of them have become invasive, causing negative impacts on biodiversity and human activities. The assessment and knowledge on the degree and scale to which forest ecosystems are invaded by non-native trees is of paramount importance for tailored policies and strategies aiming to conserve forest. By reviewing and analyzing main databases and literature and applying a three-level scale of invasion, we assessed the current and potential occurrence of twenty-five invasive non-native trees across forest ecosystems of Italy. Vulnerability to invasion substantially differed across forest categories, with riparian forests being particularly vulnerable to invasion. Many non-native trees invaded a few forest categories but showed their potential to widen their impact on other forest categories. Furthermore, some non-native species showed a recent increase of their invasive status in Italy. This review identifies the Italian forest categories and non-native trees that deserve primary attention and can support management, and allocation of funding to protect forests and limit the spread of invasive tree species.
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Cover Letter

TESAF

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Rosà (VI, Italy), March 18 2022

Dear Editors-in-Chief of *Forest Ecology and Management*,

This cover letter accompanies a copy of the manuscript entitled "Tree invasions in Italian forests" that was written in collaboration with Emilio Badalamenti and Tommaso La Mantia of the Università degli Studi di Palermo, Tommaso Sitzia of the Università degli Studi di Padova, Giuseppe Brundu of the Università degli Studi di Sassari, and Sabina Burrascano and Laura Celesti-Grapow of the Sapienza Università di Roma.
We propose here a national-wide assessment of the most invasive non-native trees in Italian forests. To the best of our knowledge, this is the first attempt for Italy or for any European country. We adopted a three-level scale with the aim to evaluate not only the current invasion level but also the potential invasion of Italian forest ecosystems by invasive non-native trees. As such, our study has relevant management implications allowing both increasing the efficiency of early detection and control strategies of the most invasive non-native trees in forests and prioritizing funding and silvicultural practices. The assessment approach adopted in this study can be easily updated as long as new information and knowledge about invasive species and forests are gained. We deem that a similar approach is of interest for international readers and stakeholders as it can be replicated in other countries allowing comparisons and information exchange, which are particularly useful for neighboring countries or affected by high trade exchanges. Furthermore, outcomes are of interest for those areas in which the analyzed tree species are non-native.
I trust that you will find our submission complete, thorough and to the appropriate standard for publication in *Forest Ecology and Management*. I confirm that the manuscript nor any parts of its content are currently under consideration or published in another journal. Should you have any questions regarding our submission, please do not hesitate to contact me.
The first and the last authors of this manuscript contributed equally and I would like to ask if both could be considered corresponding authors.

Yours sincerely,

Thomas Campagnaro (on behalf of our co-authors)
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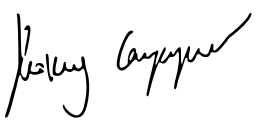

Tree invasions in Italian forests

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Highlights

- Non-native tree species invade a wide range of forest categories in Italy
- Riparian forests are particularly vulnerable to non-native tree invasion
- *Robinia pseudoacacia* and *Ailanthus altissima* are by far the most frequent invaders
- *Eucalyptus camaldulensis, Populus ×canadensis* and *Ulmus pumila* have recently spread
- Tailored strategies for the management of non-native tree species are needed

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Abstract

Many forest tree species have been moved outside their native range to provide goods and services elsewhere, but some of them have become invasive, causing negative impacts on biodiversity and human activities. The assessment and knowledge on the degree and scale to which forest ecosystems are invaded by non-native trees is of paramount importance for tailored policies and strategies aiming to conserve forest. By analyzing main databases and literature and applying a three-level scale of invasion, we assessed the current and potential occurrence of twenty-five invasive non-native trees across forest ecosystems of Italy. Vulnerability to invasion substantially

differed across forest categories, with riparian forests being particularly vulnerable to invasion. Many non-native trees invaded a few forest categories but showed their potential to widen their impact on other forest categories. Furthermore, some non-native species showed a recent increase of their invasive status in Italy. This study identifies the Italian forest categories and non-native trees that deserve primary attention and can support management, and allocation of funding to protect forests and limit the spread of invasive tree species.

Key words

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Introduction

Non-native tree species are increasingly becoming dominant components in forest ecosystems in many parts of the world (FAO 2020), thus stimulating debates and concerns about the risks associated with their generalized or unregulated use (Dickie et al. 2014, Pötzelsberger et al. 2020). A decade ago, 434 invasive non-native tree species have been recorded globally (Richardson and Rejmánek 2011, Rejmánek and Richardson 2013), but this figure requires constant updating (Rejmánek 2014). New introductions of non-native species are increasing, and this trend is expected to continue in the next future (Seebens et al. 2017, 2020). Furthermore, a higher number of non-native species, among which trees, is projected to become invasive, although after a lag phase (Early et al. 2016, Richardson et al. 2014). In Europe, 150 non-native tree species were found to cover around 8.54 million hectares, 4% of the total forest area (Brus et al. 2019). Notwithstanding these broad scale syntheses, detailed and updated information for individual countries are often missing, and this hampers early warning systems as well as concrete containment actions.

Successful non-native tree invaders most likely high metabolic rate, fast growth rate, great height, abundant seed production, early flowering, robust leaves of longer lifespan, greater duration of annual carbon gain, and wide native range (Lamarque et al. 2011, Pyšek et al. 2014, van der Sande et al. 2020, Fridley et al. 2022). However, other factors play a role in fostering the invasiveness of non-native tree species; for instance, introduction pathways and planting history can be crucial in determining the status and extent of the spread of a species in a given region (Krivánek et al. 2006, Donaldson et al. 2014) or in a specific context (Catford et al. 2022, Sapsford et al. 2020). Globally, non-native trees are introduced and spread mainly through forestry and agroforestry activities (Richardson 1998, Richardson et al. 2014, Brundu and Richardson 2016, Sitzia et al. 2016, Badalamenti et al. 2018, Brundu et al. 2020a) because of their resistance to abiotic and biotic stresses – a crucial aspect to produce valuable timber (Kjær et al. 2014, Sitzia 2014, Keča et al. 2019) – especially in times of climate change.

Even though only a minor proportion of introduced tree species become invasive, they may cause large, harmful, and long-lasting effects, whose impacts on biodiversity and human societies deserve primary attention (Pötzelsberger et al. 2020). Non-native tree species effects on ecosystem (dis)services are characterized by synergies and trade-offs among them that, in turn, are influenced by context dependencies and local factors (Castro-Díez et al. 2019, 2021). Also, the duration of the invasion can determine the impacts and spread by non-native trees (Mostert et al. 2017) hampering the timely detection of the most harmful species.

Non-native trees may invade a wide range of natural and semi-natural ecosystems, encompassing forests as well as open habitats. In Europe, non-native trees are increasingly reported to invade

forest habitats (Berg et al. 2016), with some of them being reported to exert a variety of impacts on forest structure and processes, as well as on the assemblage of different taxa (Campagnaro et al. 2018, Gentili et al. 2019, Langmaier and Lapin 2020). European forests vulnerability to plant invasions increases with the level of disturbance, fragmentation, and non-native propagule pressure (Wagner et al. 2017). The habitat-based approach is commonly adopted to understand the preferential patterns of invasive plants spread, thus having a strong influence on management and control strategies (Chytrý et al. 2008). There is large evidence that floodplain and oak-dominated woodlands, many of which are of conservation interest, are among the most invaded forest habitats (Essl et al. 2011, Berg et al. 2016, Wagner et al. 2017, Campagnaro et al. 2018, Guarino et al. 2021). Furthermore, recent research has highlighted that information on the native habitats of non-native species can provide insights into the forest types that are more likely to be invaded (van der Sande et al. 2020). Despite these findings, the context-dependency of non-native trees status, spread and impacts, indicates the need for studies conducted at fine spatial scales, such as regions and countries (Sádlo et al. 2017), finding associations between non-native trees and invaded forest types. This would allow to address control and monitoring efforts towards the most vulnerable habitats (Bonari et al. 2021) and the most invasive non-native trees (Lapin et al. 2019), thus moving towards tailored and adaptive approaches in non-native tree species management (van Wilgen and Richardson 2014).

Here, we combined the national inventory of the Italian non-native flora (Celesti-Grapow et al. 2009) and its updates, which report data for each of the 21 administrative regions, with a literature search focused on invasive non-native tree species and on their links with Italian forest categories. Based on this approach, we provide a comprehensive overview on the occurrence of invasive non-native tree species in Italy and an assessment of tree invasions in Italian forests. Our ultimate goal is to inform the prioritization of both non-native tree species and forest categories for their management at the country scale.

Materials and methods

Selection of invasive non-native tree species

We identified and selected the invasive non-native trees (INNTs) for the 21 administrative Italian regions based on: the checklist of the non-native flora of Italy (Celesti-Grapow et al. 2009); its updates (Galasso et al. 2018a, 2018b, 2018c, 2019a, 2019b, 2020a, 2020b, 2021a, 2021b), most of which included in the *Portale della Flora d'Italia* (2021) and Acta Plantarum (Longo et al. 2021) online sources; and additional non-indexed sources (e.g., Alessandrini et al. 2018). We included trees (i.e., scapose phanerophytes), woody plants bearing the resting buds higher than 200 cm from

the ground and characterized by a clearly identifiable main stem (Raunkiær 1934; Ellenberg and Mueller-Dombois 1967), that were neophytes, species introduced after 1492 (Pyšek et al. 2004). Life forms were retrieved from Acta Plantarum (Longo et al. 2021) and the global database of invasive trees and shrubs (Richardson and Rejmánek 2011) or, if necessary, upon expert opinion. According to these criteria, 25 INNTs were identified for Italy (Table 1).

121 Table 1 Overview of the 25 invasive non-native tree species considered in this study.

Invasive non-native tree species	**Species code**	**Family**	**Native range**[a]	**Year of first introduction**[b]	**Documented or potential negative impact on Italian forests**[e]
Acacia dealbata Link subsp. *dealbata*	Aca.dea	Fabaceae	SE Australia	1835	Impact outcome - Reduction in native biodiversity - Habitat degradation - Soil or sediment modification - Modification of successional patterns - Modification of nutrient pool and fluxes - Modification of food web - Primary production alteration Mechanism - Competition - Interaction with other invasive species
Acacia mearnsii De Wild.	Aca.mea	Fabaceae	SE Australia	1821	Impact outcome - Reduction in native biodiversity - Soil or sediment modification (GB pers. obs.) - Modification of nutrient pool and fluxes (GB pers. obs.) Mechanism - Competition - Interaction with other invasive species[f]
Acacia provincialis A.Camus	Aca.pro	Fabaceae	South Australia to Victoria	1862	Not documented up to now

Acacia pycnantha Benth.	Aca.pyc	Fabaceae	SE Australia	1865	Impact outcome - Reduction in native biodiversity - Primary production alteration - Modification of successional patterns - Soil or sediment modification Mechanism - Competition - Interaction with other invasive species
Acacia saligna (Labill.) H.L.Wendl.	Aca.sal	Fabaceae	SW Australia	1827	Impact outcome - Reduction in native biodiversity - Habitat degradation - Modification of successional patterns - Soil or sediment modification - Habitat or refugia replacement/loss Mechanism - Competition - Interaction with other invasive species[c]
Acer negundo L.	Ace.neg	Sapindaceae	Canada to Honduras	1780	Impact outcome - Reduction in native biodiversity - Habitat degradation - Modification of food web - Habitat or refugia replacement/loss Mechanism - Competition
Ailanthus altissima (Mill.) Swingle	Ail.alt	Simaroubaceae	China	1760	Impact outcome - Habitat or refugia replacement/loss - Habitat degradation - Reduction in native biodiversity

					- Modification of successional patterns - Soil or sediment modification - Physical disturbance Mechanism - Competition - Interaction with other invasive species - Poisoning/toxicity - Rooting/digging
Broussonetia papyrifera (L.) Vent.	Bro.pap	Moraceae	Cambodia, China, India, Japan, Laos, Myanmar, Thailand	1760	Impact outcome - Reduction in native biodiversity Mechanism - Competition - Poisoning/toxicity
Elaeagnus pungens Thunb.	Ela.pun	Elaeagnaceae	South-Central and Southeast China, Japan, Korea, Tadzhikistan	1865	Impact outcome - Reduction in native biodiversity Mechanism - Competition
Eucalyptus camaldulensis Dehnh. subsp. *camaldulensis*	Euc.cam	Myrtaceae	Australia	1832[c]	Impact outcome[3] - Reduction in native biodiversity - Habitat degradation - Soil or sediment modification (GB pers. obs.) Mechanism - Competition - Interaction with other invasive species

Juglans nigra L.	Jug.nig	Juglandaceae	Canada, USA	1760	Impact outcome[g] - Habitat degradation Mechanism - Competition
Ligustrum lucidum W.T.Aiton	Lig.luc	Oleaceae	Central & S China to Hainan, S Korea	1831	Impact outcome - Habitat degradation - Modification of nutrient pool and fluxes - Reduction in native biodiversity Mechanism - Competition
Parkinsonia aculeata L.	Par.acu	Fabaceae	S USA to N Argentina, Caribbean	1760	- Not documented up to now
Paulownia tomentosa (Thunb.) Steud.	Pau.tom	Paulowniaceae	Central & E China, S Korea	1843	Impact outcome - Reduction in native biodiversity Mechanism - Competition
Platanus ×*hispanica* Mill. ex Münchh.	Pla.his	Platanaceae	Hybrid origin	After 1551	Impact outcome[h] - Habitat degradation Mechanism - Competition
Populus ×*canadensis* Moench	Pop.x.can	Salicaceae	Hybrid origin	1907	Impact outcome[j] - Reduction in native biodiversity

					- Habitat degradation Mechanism - Competition - Hybridization[l]
Prunus laurocerasus L.	Pru.lau	Rosaceae	SE Europe to Iran	1563	Impact outcome - Reduction in native biodiversity - Habitat degradation - (Allelopathy) Mechanism - Competition
Prunus serotina Ehrh.	Pru.ser	Rosaceae	W Canada to NW USA, E Canada to Guatemala	1811	Impact outcome - Reduction in native biodiversity - (Allelopathy) Mechanism - Competition - Poisoning/toxicity
Quercus rubra L.	Que.rub	Fagaceae	Canada, USA	1803	Impact outcome - Reduction in native biodiversity - Habitat degradation - Habitat or refugia replacement/loss Mechanism - Competition

Robinia pseudoacacia L.	Rob.pse	Fabaceae	USA	1662	Impact outcome - Habitat degradation - Habitat or refugia replacement/loss - Modification of food web - Modification of nutrient pool and fluxes - Modification of successional patterns - Primary production alteration - Reduction in native biodiversity - Soil or sediment modification Mechanism - Competition - Interaction with other invasive species - Poisoning/toxicity
Robinia viscosa Vent.	Rob.vis	Fabaceae	E USA	1802	Not documented up to now
Sesbania punicea (Cav.) Benth.	Ses.pun	Fabaceae	Central & S. Brazil to NE. Argentina	1842	Impact outcome (EB pers. obs.) - Habitat degradation - Reduction in native biodiversity - Modification of nutrient pool and fluxes Mechanism (EB pers. obs.) - Competition - Interaction with other invasive species[c]
Trachycarpus fortunei (Hook.) H.Wendl.	Tra.for	Arecaceae	S Central China to N Myanmar	1834	Impact outcome - Habitat degradation - Reduction in native biodiversity Mechanism - Competition

Ulmus pumila L.	Ulm.pum	Ulmaceae	Central Asia to S Siberia and Korea	1811	Impact outcome - Reduction in native biodiversity Mechanism - Competition - Hybridization
Vachellia karroo (Hayne) Banfi & Galasso	Vac.kar	Fabaceae	Southern Africa	1821[d]	Impact outcome - Reduction in native biodiversity Mechanism - Competition

[a] POWO (2021).
[b] Maniero (2000), Maniero (2015) and references therein, unless otherwise stated.
[c] Badalamenti et al. (2018).
[d] Pasta et al. (2012).
[e] Lazzaro et al. (2020) and references therein, unless otherwise stated. The terminology on impact mechanisms and outcomes follows Blackburn et al. (2014).
[f] Brundu et al. (2019)
[g] Scatamacchia (2011).
[h] Mason (2004).
[i] Cicinelli et al. (2018).
[j] Paffetti et al. (2018).

Assessment of the invasive status

Firstly, we assessed the status of each INNT in Italian regions over time by integrating the information in the checklist of non-native flora of Italy and its updates (see above for references). These lists, compiled by national and local experts, apply a classification system of alien plant species tied to the introduction-naturalisation-invasion continuum approach (Pyšek et al. 2004). Therefore, the current definition of invasive status is predominantly based on such approach and, to date, a comprehensive risk assessment of the non-native flora of Italy is missing. Hence, invasive plant species are defined as those "*that produce reproductive offspring, often in very large numbers, at considerable distances from the parent plants, and thus have the potential to spread over a large area*" (Pyšek et al. 2004). This definition is neither based on the species actual or potential impacts, nor on prioritisation or risk assessment methods. To overcome this limitation and take into account also impact-based definitions (e.g., European Parliament and Council adopted Regulation (EU) No 1143/2014) that imply being ecologically detrimental (Lemoine and Svenning 2022), we applied an integrated approach considering the status in the national list as well as the documented and potential impacts for the Italian territory (see Table 1). Furthermore, when referring to naturalized species, we intend species "*that sustain self-replacing populations for at least 10 years without the direct intervention of people […] by the recruitment of seeds or ramets […] capable of independent growth*" (Pyšek et al. 2004).

Secondly, we integrated this assessment with recent studies reporting non-native species management at the country scale to account for species inclusion in regional legislations (Brundu et al. 2020b), and priority species that have been suggested as suitable candidates to be included in a national list according to Regulation (EU) n. 1143/2014 (Lazzaro et al. 2019). Our assessment considered non-native tree species reported spreading outside planting sites in Europe (Brus et al. 2019), the checklists of woody invasive non-native species in the world (Richardson and Rejmánek 2011, Rejmánek and Richardson 2013) and the global risk score (Randall 2017).

Classification of the forest categories

A variety of forest classifications exist and are commonly adopted in Italy, encompassing different spatial scales and objectives: from the European classification used for assessing indicators of sustainable forest management (Barbati et al. 2014), to the national classification system used in the inventory of forests and forest carbon pools (Gasparini and Tabacchi 2011), up to regional classifications (Del Favero 2004, Del Favero 2008, Del Favero 2010). However, research on non-native tree species has rarely referred to encoded forest types or categories, but rather to the dominant tree species. Thus, for the purpose of the present study, we adopted an original

166 classification of forest categories (Table 2). We also included a focus on spontaneous urban forests,
167 which are particularly susceptible to the spread of non-native tree species, due to high propagule
168 pressure from ornamental non-native trees and plantations, and the high level of disturbance.
169 The spatial extent of each forest category was based on Gasparini and Tabacchi (2011), except for
170 mountain pine forests, for which we considered the area reported in last national reporting
171 according to art. 17 of the Habitats Directive. We used the quartile distribution of the categories
172 extent data to define three broad classes: narrow, medium, large.
173
174 Table 2. Forest categories used to assess the invasion of non-native trees in Italy, their dominant
175 woody species and class of spatial extent.

Forest category	**Dominant woody species**	**Spatial extent**
Subalpine and temperate scrublands	*Alnus alnobetula, Calluna vulgaris, Rhododendron hirsutum, Salix* sp.pl., *Vaccinium myrtillus*	Medium
Maquis, Mediterranean scrublands	*Arbutus unedo, Erica* sp.pl., *Myrtus communis*, *Pistacia lentiscus*, *Phillyrea* sp.pl., *Prunus spinosa* subsp. *spinosa*, *Rhamnus alaternus*	Large
Mediterranean pine forests	*Pinus halepensis* subsp. *halepensis*, *Pinus pinaster* subsp. *pinaster*, *Pinus pinea*	Medium
Oak-hornbeam and hornbeam forests	*Carpinus betulus*, *Quercus robur*	Narrow
Holm oak forests	*Quercus ilex*	Medium
Cork oak forests	*Quercus suber*	Medium
Downy oak forests	*Quercus pubescens* s.l.	Large
Sessile oak forests	*Quercus petraea*	Narrow
Pedunculate oak forests	*Quercus robur*	Narrow
Turkey oak forests	*Quercus cerris*	Large
Other oak forests	*Quercus frainetto, Quercus trojana*	Narrow
Chestnut forests	*Castanea sativa*	Large
Manna ash-hornbeam forests	*Fraxinus ornus, Ostrya carpinifolia, (Quercus pubescens)*	Large
Maple-European ash and Maple-Lime forests	*Acer pseudoplatanus*, *Fraxinus excelsior*, *Tilia cordata*, *Tilia platyphyllos*	Medium
Pioneer forests	*Acer campestre, Betula pendula, Corylus avellana, Populus tremula*, *Ulmus minor* s.l.	Narrow
Beech forests	*Fagus sylvatica*	Large
Mountain pine forests	*Pinus mugo*	Medium

Black pine forests	*Pinus nigra* s,l.	Medium
Scots pine forests	*Pinus sylvestris*	Medium
Silver fir forests	*Abies alba*	Narrow
Norway spruce forests	*Picea abies*	Medium
Larch, Larch-Swiss pine, and Swiss pine forests	*Larix decidua, Pinus cembra*	Medium
Riparian forests	*Alnus glutinosa, Alnus incana, Fraxinus angustifolia, Platanus orientalis, Populus* sp.pl., *Salix* sp.pl.	Medium
Forests dominated by other conifers (including plantations)	*Cedrus* sp.pl., *Cupressus* sp.pl., *Pinus heldreichii* subsp. *leucodermis, Taxus baccata*	Medium
Forests dominated by other broadleaves	*Alnus cordata, Ceratonia siliqua, Ilex aquifolium, Laurus nobilis*, *Olea europaea* var. *sylvestris*	Medium

Assessment of the current and potential invasion level of Italian forests by invasive non-native trees

The current and potential invasion level of forest categories by INNTs was ranked from 0 (category with no evidence of current or potential invasion) to 3 (category massively invaded). Intermediate values have been attributed when an INNT is not widely invading the category in Italy (score = 2) or it has solely been observed invading the category outside Italy (score = 1). The difference between score 3 and score 2 accounted for the level and the temporal dynamics of the invasion process in different Italian regions. The score 1 was based on the *invasive elsewhere* criterion, i.e., the documented establishment of a given non-native tree species in one category outside Italy was considered as a reliable proxy of the potential invasion of the same category in Italy.

Table 3 - Scale for the level of invasion of forest categories by non-native trees applied in this assessment for Italy.

Score	**Brief description**	**Full description**
0	Not currently invaded and with low invasibility	Forest category not invaded in Italy, Europe or elsewhere and with no or very low potential to be invaded in the future
1	Potentially invasible	Forest category invaded outside Italy and prone to be invaded in Italy
2	Moderately invaded	Forest category currently invaded in a limited portion of

		the national range of the forest category
3	Massively invaded	Forest category commonly invaded over large portions of the national range of the forest category

The score was associated with each combination of category and species based on bibliographic sources and expert knowledge acquired through on-purpose meetings (Supplementary material 1). Primarily, we considered scientific and grey literature reporting information on the spread of INNTs in specific categories in Italy: (i) manuals or atlases, (ii) large scale studies about introduced tree species including Italy in their study area; (iii) studies addressing the invasion by individual INNTs, and (iv) technical documents. Secondarily, especially for non-native trees with a current limited range in Italy, the scientific literature mostly derived from an *ad-hoc* search on Google scholar of their scientific and common names, including the most used synonyms, in association with the forest categories of this study. Only scientific articles explicitly referring to spontaneous (*i.e.*, not planted) individuals of INNTs were considered.

We also evaluated INNTs found in urban forests and whether they were the stand-dominant species or not, based on Italian literature and personal observations.

Statistical analysis of the invasion level scores

We used non-metric multidimensional scaling (NMDS) based on the Cao index of dissimilarity in the level of invasion of each category (function *metaMDS* in the R package *vegan*; R Development Core Team 2021). We correlated (Spearman rho coefficient) the number of INNTs with each score different from 0 per category with the area of that category. We also correlated the number of categories per score to which an INNT was combined with: (i) the date of first introduction; (ii) the number of regions where the tree species was reported as invasive, (iii) or as with self-replacing populations in 2021 (Table 4).

Results

Invasive non-native tree species in Italy

Our systematic overview pointed out an increase in the number of INNTs, from 13 to 25, in 13 years (Table 4, Supplementary material 2). Fabaceae family was by far the most represented (10 taxa, 40% of all tree species); in fact, except from Rosaceae (represented by 2 taxa), all the other families were represented by a single species. Origin was almost equally distributed among

218 temperate Asia (32%), Australia and North America (24%). The only two species with tropical and
219 subtropical origin were *Parkinsonia aculeata* and *Sesbania punicea.*. The majority of tree species
220 was introduced to Italy during the nineteenth century (> 60%), and 20% of the species during the
221 eighteenth century. Older introductions (before 1700) accounted for slightly more than 10% of the
222 species, while only one species was introduced in the last century.
223 *Ailanthus altissima* and *Robinia pseudoacacia* were invasive in most of the national territory (more
224 than 17 regions), while most species (about 40%) were invasive in a single Italian region. When
225 considering naturalized and invasive status together, six species (*Acer negundo*, *Ailanthus altissima*,
226 *Broussonetia papyrifera*, *Ligustrum lucidum*, *Platanus hispanica* and *Robinia pseudoacacia*)
227 occurred in most regions, while only two species were limited to a single region (*Acacia mearnsii*
228 and *Robinia viscosa*). The species which registered the highest increase in the number of regions
229 with self-replacing populations were *Ulmus pumila* (+6 regions), *Eucalyptus camaldulensis* and
230 *Populus* ×*canadensis* (+4 regions for both). About half of the species were found at least as
231 naturalized in two or three additional regions compared to the 2009 situation.
232 Importantly, about half of the species undergo some type of restrictions or are listed according to
233 regional legislation (56%; Table 4), while less were listed among the national priorities with few
234 overlaps between these two categories. Five priority species were still not legally considered
235 (*Acacia mearnsii*, *Acacia pycnantha*, *Elaeagnus pungens*, *Parkinsonia aculeata* and *Vachellia*
236 *karroo*). *Acacia mearnsii* and *Acacia pycnantha* were recorded as invasive in few regions only
237 recently.
238 Except for *Robinia viscosa* (that was not assessed), all species have been reported as invasive
239 globally, mostly with high or extreme risk scores (64%), with only two species (*Elaeagnus pungens*
240 and *Platanus hispanica*) reported with a low risk.
241

Table 4. Status of the non-native tree species considered in this study with additional information about legislative and management issues as well as their global relevance. §: self-replacing populations include "naturalized" and "invasive" status according to Pyšek et al. (2004). In round brackets, the number of regions where each tree species is regarded as invasive in Italy is reported.

Species	Family	Number of Italian regions with self-replacing populations§ (2009)[a]	Number of Italian regions with self-replacing populations§ (2018)[b]	Number of Italian regions with self-replacing populations§ (2021)[c]	Regulated by regional legislation[d]	Candidate non-native plants for national list[e]	European Countries reporting spread outside planting sites[f]	Invasive non-native species of Union concern[g]	Global invasive species[h]	Global Risk Score (rating)[i]
Acacia dealbata subsp. *dealbata*	Fabaceae	3 (2)	4 (2)	5 (2)	-	-	1	-	X	25.9 (high)
Acacia mearnsii	Fabaceae	1 (1)	1 (1)	1 (1)	-	X	n.r.	-	X	25.9 (high)
Acacia provincialis	Fabaceae	1 (1)	2 (1)	2 (1)	-	-	0	-	X	7.9 (medium)
Acacia pycnantha	Fabaceae	0 (0)	2 (1)	2 (1)	-	X	0	-	X	9.6 (medium)
Acacia saligna	Fabaceae	7 (3)	8 (5)	8 (5)	X	X	1	X	X	34.6 (extreme)
Acer negundo	Sapindaceae	10 (4)	12 (6)	12 (6)	X	-	8	-	X	34.6 (extreme)
Ailanthus altissima	Simaroubaceae	20 (20)	20 (20)	20 (20)	X	-	10	X	X	43.2 (extreme)

Broussonetia papyrifera	Moraceae	13 (3)	14 (4)	14 (4)	X	-	1	-	X	25.9 (high)
Elaeagnus pungens	Elaeagnaceae	2 (0)	4 (1)	4 (1)	X	X	n.r.	-	X	3.6 (low)
Eucalyptus camaldulensis subsp. *camaldulensis*	Myrtaceae	2 (0)	6 (1)	6 (1)	X	-	0	-	X	25.9 (high)
Juglans nigra	Juglandaceae	0 (0)	2 (1)	3 (1)	-	-	0	-	X	12.9 (medium)
Ligustrum lucidum	Oleaceae	9 (0)	12 (2)	12 (2)	X	-	0	-	X	43.2 (extreme)
Parkinsonia aculeata	Fabaceae	1 (1)	2 (1)	3 (2)	-	X	n.r.	-	X	64 (extreme)
Paulownia tomentosa	Paulowniaceae	5 (0)	7 (1)	7 (1)	X	-	0	-	X	34.6 (extreme)
Platanus hispanica	Platanaceae	8 (0)	10 (0)	11 (1)	-	-	0	-	X	3.36 (low)
Populus ×canadensis	Salicaceae	5 (0)	8 (0)	9 (2)	-	-	2	-	X	16.8 (high)
Prunus laurocerasus	Rosaceae	2 (1)	4 (3)	5 (3)	X	-	n.r.	-	X	19.2 (high)
Prunus serotina	Rosaceae	3 (3)	4 (3)	4 (3)	X	X	9	-	X	43.2

										(extreme)
Quercus rubra	Fagaceae	3 (2)	4 (2)	4 (2)	X	X	3	-	X	25.9 (high)
Robinia pseudoacacia	Fabaceae	20 (17)	20 (17)	20 (17)	X	-	17	-	X	64.0 (extreme)
Robinia viscosa	Fabaceae	0 (0)	1 (1)	1 (1)	-	X	0	-	-	Not assessed
Sesbania punicea	Fabaceae	0 (0)	2 (0)	3 (2)	-	-	-	-	X	8.64 (medium)
Trachycarpus fortunei	Arecaceae	3 (2)	5 (3)	5 (3)	X	X	0	-	X	17.3 (high)
Ulmus pumila	Ulmaceae	2 (0)	7 (2)	9 (2)	X	-	1	-	X	25.9 (high)
Vachellia karroo	Fabaceae	4 (0)	5 (0)	5 (1)	-	X	0	-	X	38.4 (extreme)

[a] Celesti-Grapow et al. (2009)
[b] Galasso et al. (2018a)
[c] Longo et al. (2021), Portale della Flora d'Italia (2021), Galasso et al. (2021a), and Galasso et al. (2021b)
[d] Brundu et al. (2020b)
[e] Lazzaro et al. (2019)
[f] Brus et al. (2019); n.r.: not reported
[g] pursuant to Regulation (EU) n. 1143/2014, and included in the Commission Implementing Regulation (EU) 2016/1141, 2017/1263 or 2019/1261
[h] Richardson and Rejmánek (2011) and Rejmánek and Richardson (2013)
[i] Randall (2017)

Invasion of forest categories by non-native trees in Italy

Forest categories largely differed in the number of associated INNTs. Riparian forests were by far the most invaded forest category with 16 INNTs, accounting for more than 60% of all INNTs (Figure 1). Pedunculate oak forests, oak-hornbeam and hornbeam forests, maple-European ash and maple lime forests, Mediterranean maquis and chestnut forests hosted more than 10 INNTs. Only three categories were invaded by only one species (other oak forests, forests dominated by other conifers) or by none (mountain pine forests).

The categories with the highest number of potentially invading species (score 1) were: pedunculate oak forests (n = 6), beech forests (n = 5), pioneer forests (n = 4), maple-European ash and maple-lime forests (n = 3). For two categories (other oaks forests and silver fir forests), we only found one potentially invading tree species each.

Figure 1: Number of non-native tree species invading or potentially invading each forest category in Italy. The scores associated with each group of species are indicated by different shades of green.

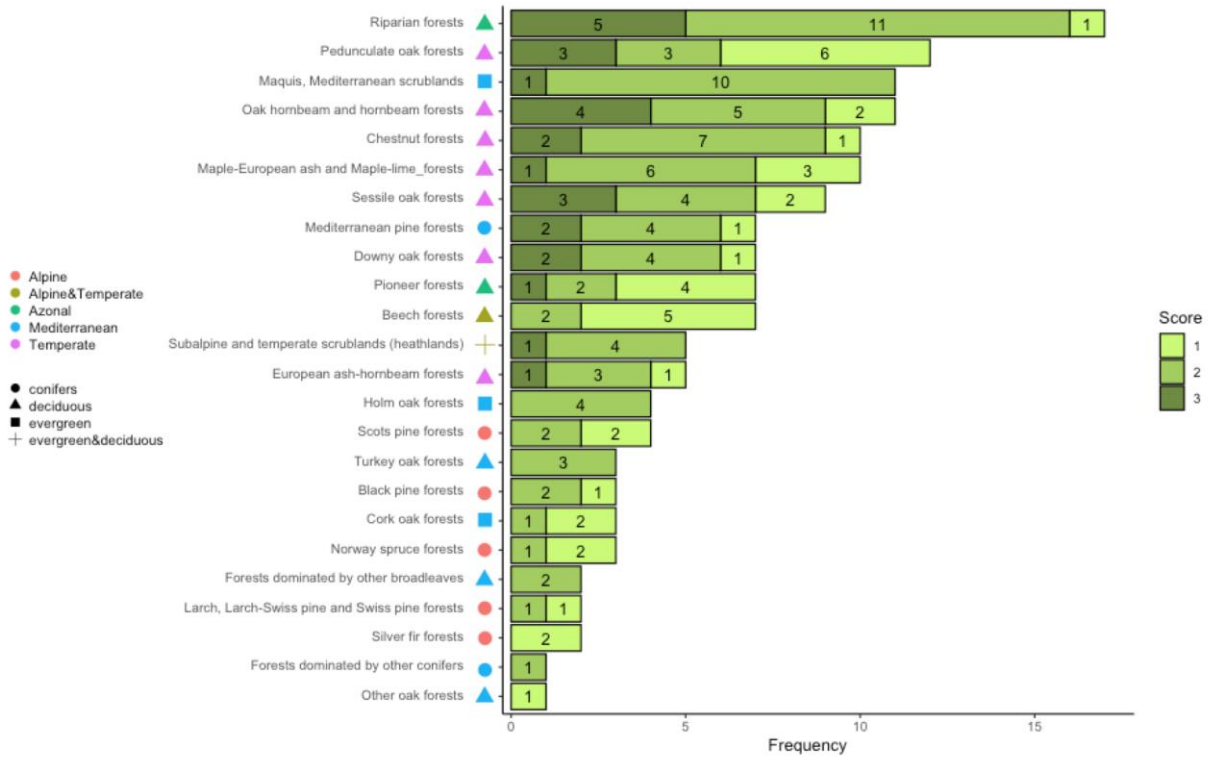
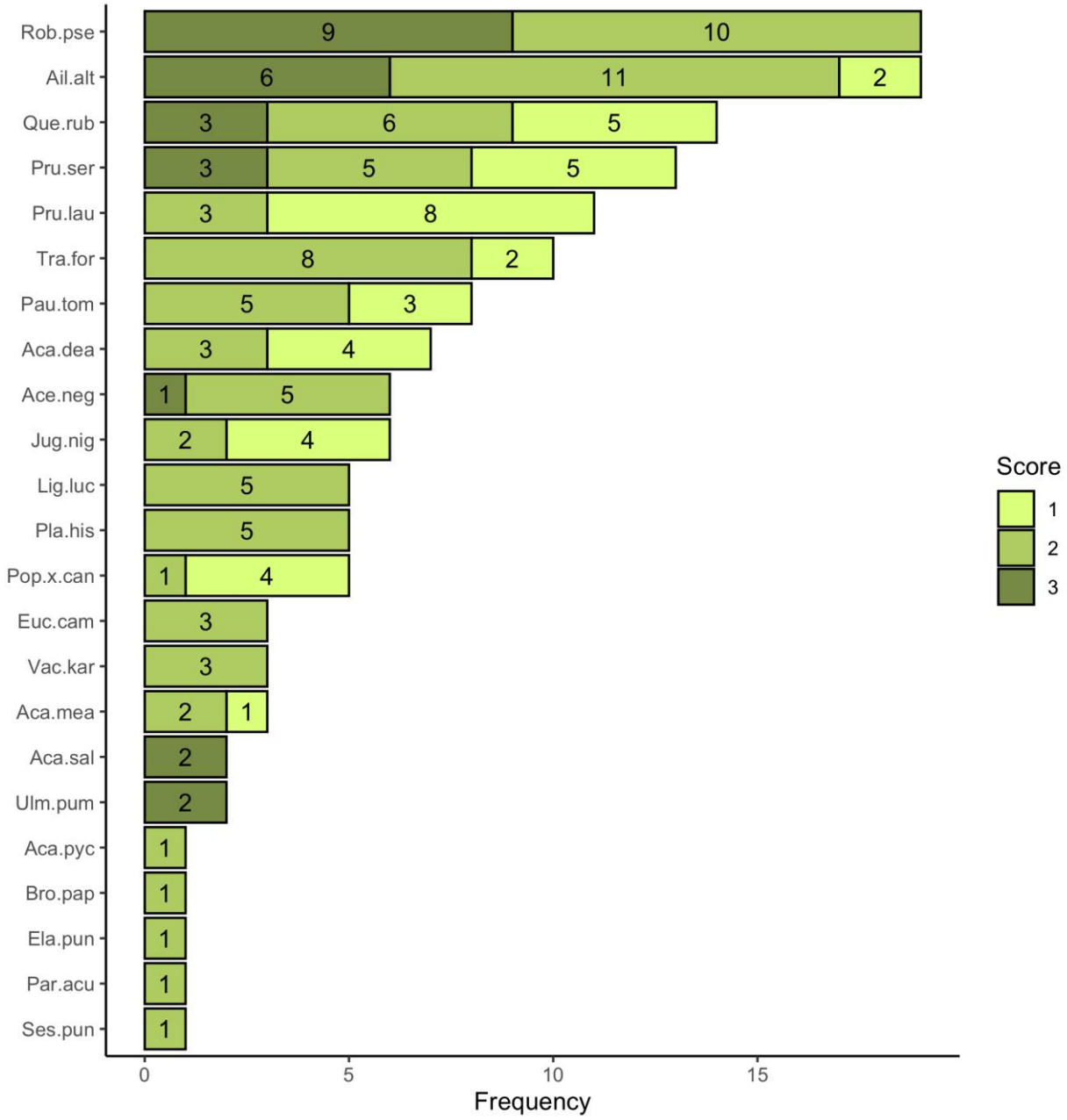


Figure 2: Number of forest categories invaded or potentially invaded by non-native tree species (see codes reported in Table 1) in Italy. The scores associated with each group of species are indicated by different shades of green.



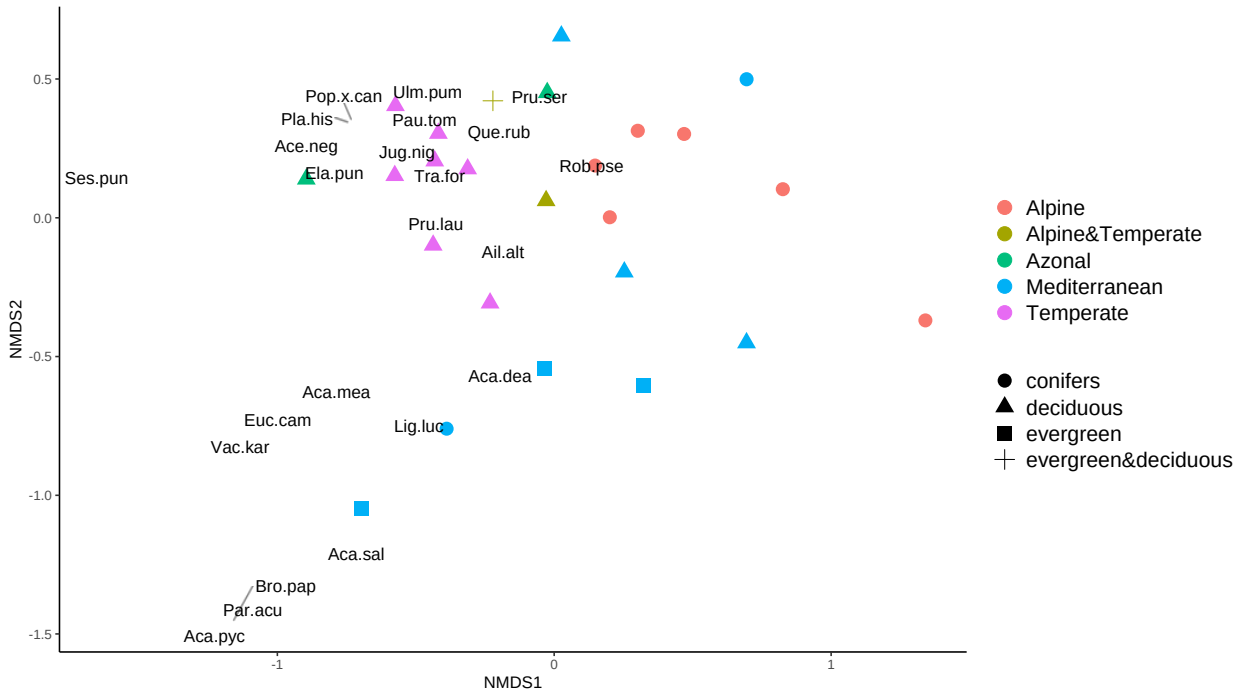
The non-native tree species invading the highest number of categories were *Robinia pseudoacacia* and *Ailanthus altissima* (n=19 and n=17, respectively), affecting about three quarters of all forest categories (Figure 2). The other INNTs listed by decreasing number of invaded categories were *Quercus rubra* (n=9), *Prunus serotina* (n=8), *Trachycarpus fortunei* (n=8), *Acer negundo* (n=6), and *Ligustrum lucidum*, *Paulownia tomentosa*, and *Platanus hispanica* (n=5 each). Fourteen INNTs are currently invading 1 to 3 forest categories. Finally, two species did not occur in Italian forests (*Acacia provincialis* and *Robinia viscosa*).

Some species have mainly the potential to invade rather than being currently invading Italian forests. For instance, *Prunus laurocerasus* invaded eight forest categories outside Italy, thus representing a potential threat for the same forest categories in Italy. The other tree species for

which we found a higher number of potentially invaded categories were *Prunus serotina* and *Quercus rubra* (n=5 for both). For *Acacia dealbata*, *Juglans nigra* and *Populus ×canadensis*, which were invasive only in a few forest categories, we found a relatively high number of forest categories potentially invasible (n=4). Importantly, we also found evidence of potential invasion even by widespread invasive species such as *Ailanthus altissima*. Urban forests were commonly composed of INNTs. In fact, we found that 20 out of the 25 species (80%) can be found in forest stands in urban settings, where seven of them were found to be able to dominate the tree layer.

The NMDS ordination highlighted a group of non-native species mostly invading Mediterranean evergreen broadleaf and conifer categories (*Acacia dealbata*, *Acacia saligna* and *Ligustrum lucidum*) while a more conspicuous group of non-native trees were linked to temperate deciduous forests (Figure 3). The majority of the forest categories occurred in Alpine areas, as well as Mediterranean deciduous were scarcely associated with INNTs.

Figure 3: NMDS ordination of forest categories (symbols), classified based on main biogeographical occurrence (Alpine, Alpine and temperate, azonal, Mediterranean, temperate indicated by different colors) and main tree species character (conifers, deciduous, evergreen, evergreen and deciduous indicated by different symbols), and non-native trees (see codes reported in Table 1) invasion level.



The number of categories with a score 3 for a specific INNT was positively correlated with the number of regions where the same species was indicated as invasive. Whereas, the number of categories with a score 2 and a score 3 for a specific INNT was positively correlated with the number of regions where the same species was reported as naturalised or invasive. The number of INNTs with score 1 per category was negatively correlated to the spatial extent of the category (Table 5), indicating that forest categories with a narrow range are also those subject to higher potential invasion risk.

Table 5: Spearman correlation (rho) values ($p \leq 0.05$ as *; $p \leq 0.01$ as **; $p \leq 0.001$ as ***) between the number of invasive non-native trees and forest categories by invasion scores, and introduction time, occurrence and status in administrative regions, and spatial extent respectively.

		Ys. from 1st introduction	No. of regions as invasive	No. of regions as self-replacing populations			Category's spatial extent
Score 1	**No. of FCs**	0.050	0.152	-0.099	**Score 1**	**No. of INNTs**	-0.402*
Score 2		0.324	0.352	0.452*	**Score 2**		0.263
Score 3		0.355	0.651***	0.416*	**Score 3**		-0.113

Discussion

We found increasing trends in the number of invasive non-native tree species and invaded regions by INNTs in Italy. Given these trends, understanding the invasion patterns of non-native tree species in different forest categories at the country scale is crucial to plan and adopt adequate management strategies to prevent and/or mitigate their detrimental effects on biodiversity and ecosystem services. Here, we identified the INNTs already established within a high number of forest categories in different Italian regions, along with those which registered the highest increase in the number of affected regions, thus suggesting an increasing trend in their spread in Italy. By combining information on invasive non-native tree species and invaded forest categories in Italy, we highlighted specific associations between invasive non-native species and forest categories that may help identify species and forest categories with a higher need for prevention and control measures to tackle invasive spread (Catford et al. 2012). Furthermore, here we give an insight of the potential impacts that the main non-native tree species have on forest ecosystems.

Most invaded forests

We found evidence of a large variability in the vulnerability of different forest categories to the invasion by non-native tree species in Italy. This was partly known (see focus on habitat types of Community interest by Angelini et al. (2016) and Lazzaro et al. (2020)), but still not comprehensively assessed. In general, forest categories occurring in plain and hilly areas hosted a higher number of non-native trees than montane forests.

Deciduous, broadleaved-dominated forests were the most invaded. Maquis and Mediterranean scrublands, and riparian, chestnut, and oak-hornbeam and hornbeam forests registered the highest number of non-native species. Most of these forest categories have been already highlighted as those most invaded in Europe (Campagnaro et al. 2018, Wagner et al. 2017) and in other parts of the globe (Yelenik et al. 2004). For instance, the particularly worrying condition of riparian forests, that have by far the highest number of non-native tree species in this study, represents a widely observed pattern at the global and European scale (Langmaier and Lapin 2020, Railoun et al 2021). Indeed, several factors make riparian ecosystems particularly vulnerable to the spread of INNTs such as the peculiar disturbance regime, high light availability, frequent nutrient input, and the proximity to water that acts as a vector of transport for plant propagules (Hood and Naiman 2000, Chytrý et al. 2019). Conversely, other highly invaded forest categories in this study have been less studied and reported in the literature. For example, maquis has been seldom reported among those highly invasible (Guarino et al. 2021) and Mediterranean forests were recently reported to host fewer non-native species than temperate forests (Wagner et al. 2021). Indeed, the biotic resistance of Mediterranean woodlands to invasive plant species has been often invoked (FAO and Plan Bleu 2018). The contrasting evidence reported in our study points to the need for cautious assessments of the invasion risk of natural ecosystems.

Many forest categories were found to have the potential of hosting some of the non-native tree species we analysed, pointing to an invasion threat for the future especially in light of the forecasted climate and land use changes. Pedunculate oak and beech forests may be the most affected and have been recently highlighted among hotspots of non-native species in Europe (Wagner et al. 2021). While pedunculate oak forests cover a small area mainly in plain areas and low hills, beech forests are among the most widespread forests in Italian mountain areas (Gasparini and Tabacchi 2011). On the one hand, the narrow cover and potential changes in disturbance regimes are very worrying for pedunculate oak forests; on the other hand, changes in climatic conditions could trigger stronger invasions in beech forests (Kleinbauer et al. 2010).

Most common invasive alien trees in Italian forests

As expected, the species most frequently recorded in Italian forest categories were *Ailanthus altissima* and *Robinia pseudoacacia*, which are responsible for different documented impacts on biodiversity and ecosystem services in Italy (e.g., Benesperi et al. 2012, Montecchiari et al. 2020, Celesti-Grapow and Ricotta 2021). Both species, in addition to being the most widespread over the national territory, received policy and legal attention, with *Ailanthus altissima* being listed as of Union concern. Indeed, they dominate in large parts of Italian forested landscapes, even within protected areas (e.g., Euganean hills), and show little or no potential to invade other forest categories, suggesting that are occupying most of their current non-native range in Italy.

Differently, many species still not widespread in Italian forests were found to have the potential to spread into different forest categories. *Prunus laurocerasus* was the species with the highest number of potentially invasible forest categories, but also other species with different ecological characteristics, such as *Acacia dealbata*, *Juglans nigra*, *Quercus rubra*, *Populus ×canadensis*, and *Prunus serotina* showed the potential to invade several other forest categories. Overall, except for some species that, up to now, mainly invaded open habitats (*Acacia provincialis*, *Robinia viscosa*) or have already invaded most of the forest categories (*Robinia pseudoacacia*), most non-native tree species could expand on different forest categories.

Climate change may drive further invasion by many non-native trees, as already highlighted for *Acer negundo*, *Quercus rubra* and *Robinia pseudoacacia* in Europe (Kleinbauer et al. 2010, Dyderski et al. 2018). The forest categories most likely to be at risk in Italy would be those reported to be invaded in other European countries or those where a further expansion may be possible over the entire national territory. However, under a progressively warmer climate, non-native species are likely to increase their range where the limiting factor is represented by low temperatures rather than in areas where plants are limited by high temperatures. Therefore, while certain species may expand in Mediterranean forests, others, such as *Robinia pseudoacacia* (Puchałka et al. 2021) or *Acer negundo*, may face a decline in potential niches within these forest categories. In fact, several thermophilous tree species could expand in currently mild environments (*Acacia dealbata* and *Prunus laurocerasus*), also favored by the reduction in frost risk, while others may be favored by the increase in temperature in more mesic conditions and in mountain areas (*Prunus serotina* and *Quercus rubra*), as already suggested by different studies investigating relationships between non-native plants invasion and climate (Celesti-Grapow et al. 2016, Dainese et al. 2017). We also found evidence of very recent naturalization processes by INNTs both in temperate and Mediterranean ecosystems. This is the case for *Ulmus pumila* (Prosser and Bertolli 2015) and *Eucalyptus camaldulensis* (Badalamenti et al. 2018), respectively.

On the one hand, the invasion by some species (e.g., *Populus ×canadensis, Sesbania punicea and Ulmus pumila*), can be just a matter of time, with their limited invasive range depending on the short time since introduction, and the likely presence of a lag phase. On the other hand, the high number of potentially invasible forest categories (>70% of INNTs in at least one forest category) defines a wide range of potential future invasions and range expansions. For instance, *Eucalyptus camaldulensis*, *Juglans nigra*, *Ligustrum lucidum*, *Platanus hispanica*, *Populus ×canadensis*, *Prunus laurocerasus*, and *Sesbania punicea* showed a relatively large increase in the occurrence in Italian regions during the last 12 years (at least +3 regions) and have the potential to expand in different forest categories.

Management implications

Given the potential benefits of many non-native trees, a general ban of their use in the whole country would generate socio-economic conflicts. For this reason, strategies for a sustainable use of non-native tree species should be tailored at the country scale, besides accounting for the global and European guidelines (Brundu and Richardson 2016, Brundu et al. 2020a). Measures aiming at reducing the invasion risk, mitigating the related impacts and restoring habitat structure and functions should be planned accounting for the degree of invasibility and the conservation concern of forest categories, as well as for the characteristics of the invasive non-native species related to that specific forest category (Richardson et al. 2007; Sádlo et al. 2017; Sitzia et al. 2016).

At least three main management options could be considered depending on the initial condition. For forest categories that are already affected by several non-native trees, silvicultural practices and management options should mainly consider controlling and reducing biotic and abiotic factors favoring their further diffusion, e.g., limit vegetation and soil disturbance. While forest categories currently moderately invaded, i.e., by a few non-native trees, local eradication and prevention actions could stop, reduce or avoid the development and spread of non-native trees. Finally, for forest categories showing only a potential for non-native trees invasion, monitoring and prevention measures should be prioritized.

Also the information on invasive non-native trees, and on the number of forest categories they invaded has strong management implications, e.g., in risk assessment procedures (Bindewald et al. 2021). Non-native trees that are occurring in many forest categories, due to their wide presence, may be the focus of a general control of their spread. Species invading one or few forest categories should be prioritized when these are forest habitat types of particular conservation and scientific interest. When information on individual forest categories is lacking, attention should be given to tree taxa that are showing an increasing occurrence in Italian regions

since they may have the potential of invading several forest categories. These species should be monitored in experimental sites that allow for testing the effects of local eradication or control silvicultural actions.

Our assessment could provide useful information for all stakeholders involved in the management of forest areas, within protected areas (e.g., Natura 2000 sites), or in the definition of advanced national or regional legislative tools to prevent the spread or mitigate the negative effects of invasive plant species. Indeed, the array of species and invaded forest category indicate that the control of non-native trees requires an integrated management strategy including different silvicultural interventions (Sitzia et al. 2016, Badalamenti et al. 2018b).

Limitations of the study

We acknowledge that the classification of forest resources here reported is subjective and different forest classification schemes may give different outcomes. However, we adopted a classification sufficiently detailed at the tree species level, considering and taking into account the large variability in structure, composition and bioclimate, which characterizes Italian forests. Furthermore, the need to adopt a slender classification suggests merging some forest categories including different woody species. While in some cases we included species belonging to the same bioclimatic belt (e.g., Mediterranean pines), in other cases this was not possible (e.g., shrublands occurring in different biogeographical contexts).

The reliability of our analysis depended on the availability and quality of information across the multiple sources we considered. The spatial extent and the geographical distribution of the forest categories in Italy and elsewhere, certainly influenced the likelihood of the interaction with INNTs. Thus, the finding of some forest categories hosting a very low number of invasive non-native trees may be simply the result of a narrow distribution range. Another critical issue was the attribution of INNTs to the forest categories occurring outside Italy. This was particularly true for some tree species (e.g., *Fagus sylvatica* or *Pinus sylvestris*), which take part in very different forest communities throughout their European distribution range, thus making it difficult to use the information retrieved from literature outside Italy.

Conclusions

This is the first study that assessed the invasion status of Italian forest categories by considering the main INNTs. The integration of national databases and scientific evidence reported in the literature on the invasion of non-native trees can give an overview of this pressure on different forest categories. Furthermore, the identification of potentially invasible forests can give an idea of the level of future threat posed by non-native trees. Our results help identify which forest

categories and non-native trees should deserve primary attention and could inform management and funding priorities to protect forests from invasive non-native tree species uncontrolled spread. This information will be the basis for a shared framework to tackling tree invasions in forests at the national level that integrates EU and national regulations. This approach could be replicated in other countries where an assessment of forest invasions is lacking. Future studies should target the impact on biodiversity, particularly by focusing on the most vulnerable forest categories and the most worrying non-native tree species, as well as on the potentially most vulnerable forest categories.

CRediT authorship contribution statement

Thomas Campagnaro: Conceptualization; Methodology; Investigation; Data curation; Validation; Formal analysis; Visualization; Project administration; Roles/Writing - original draft; Writing - review & editing. **Giuseppe Brundu:** Methodology; Validation; Writing - review & editing. **Sabina Burrascano:** Methodology; Validation; Formal analysis; Writing - review & editing. **Laura Celesti-Grapow:** Methodology; Validation; Writing - review & editing. **Tommaso La Mantia:** Conceptualization; Validation; Writing - review & editing. **Tommaso Sitzia:** Conceptualization; Validation; Writing - review & editing. **Emilio Badalamenti:** Conceptualization; Methodology; Investigation; Data curation; Validation; Formal analysis; Visualization; Project administration; Roles/Writing - original draft; Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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Figure 1

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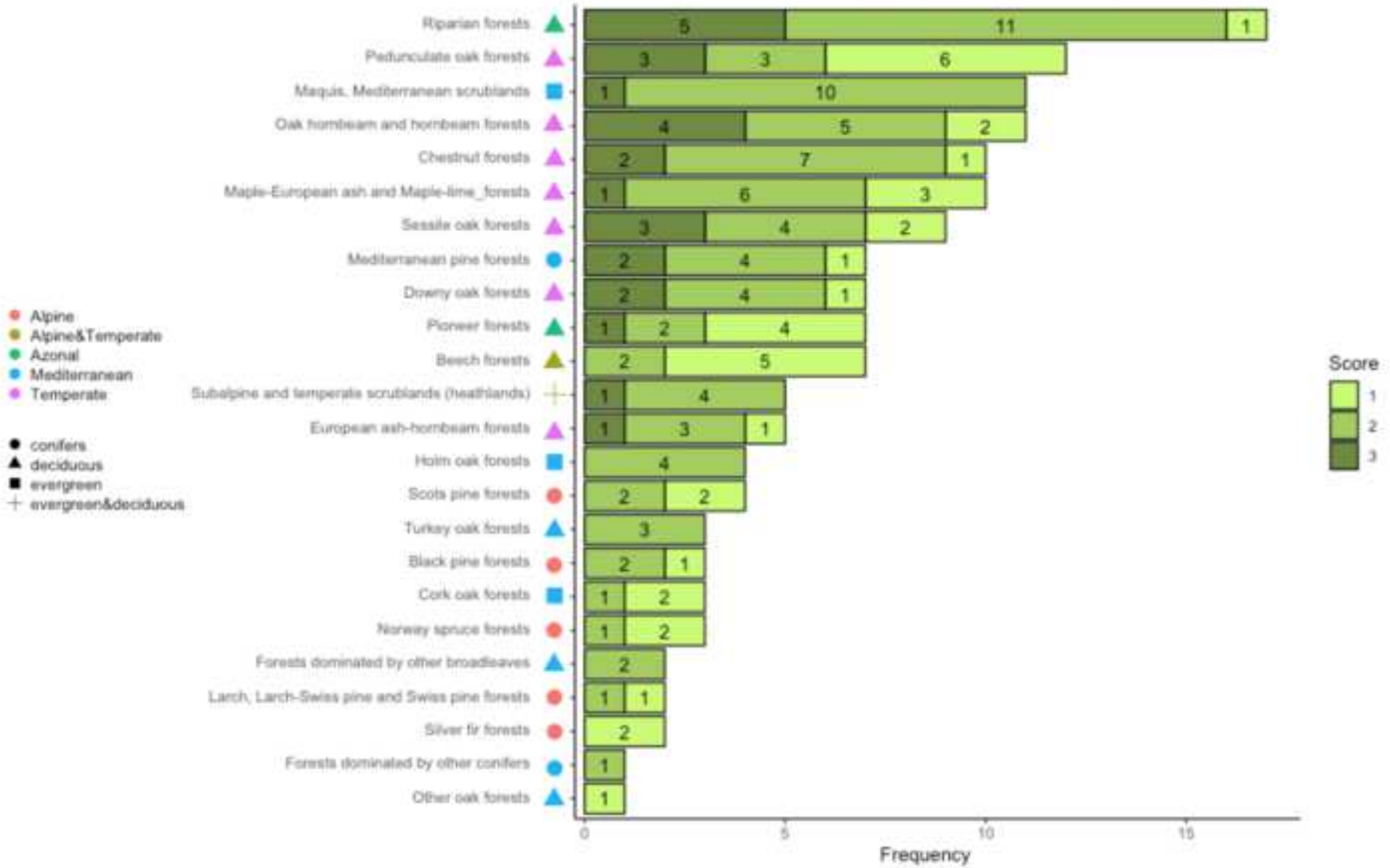

Figure 2

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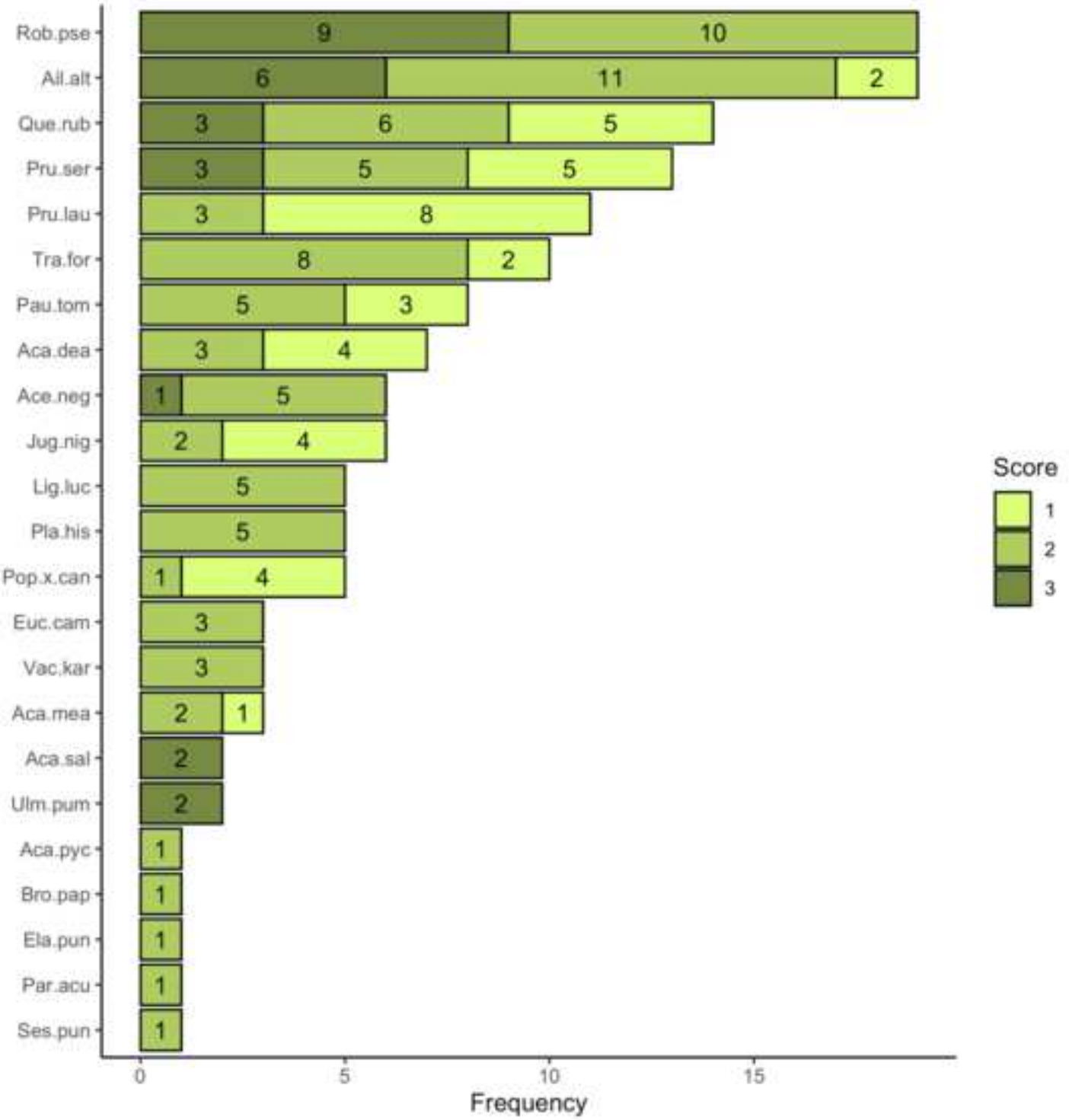
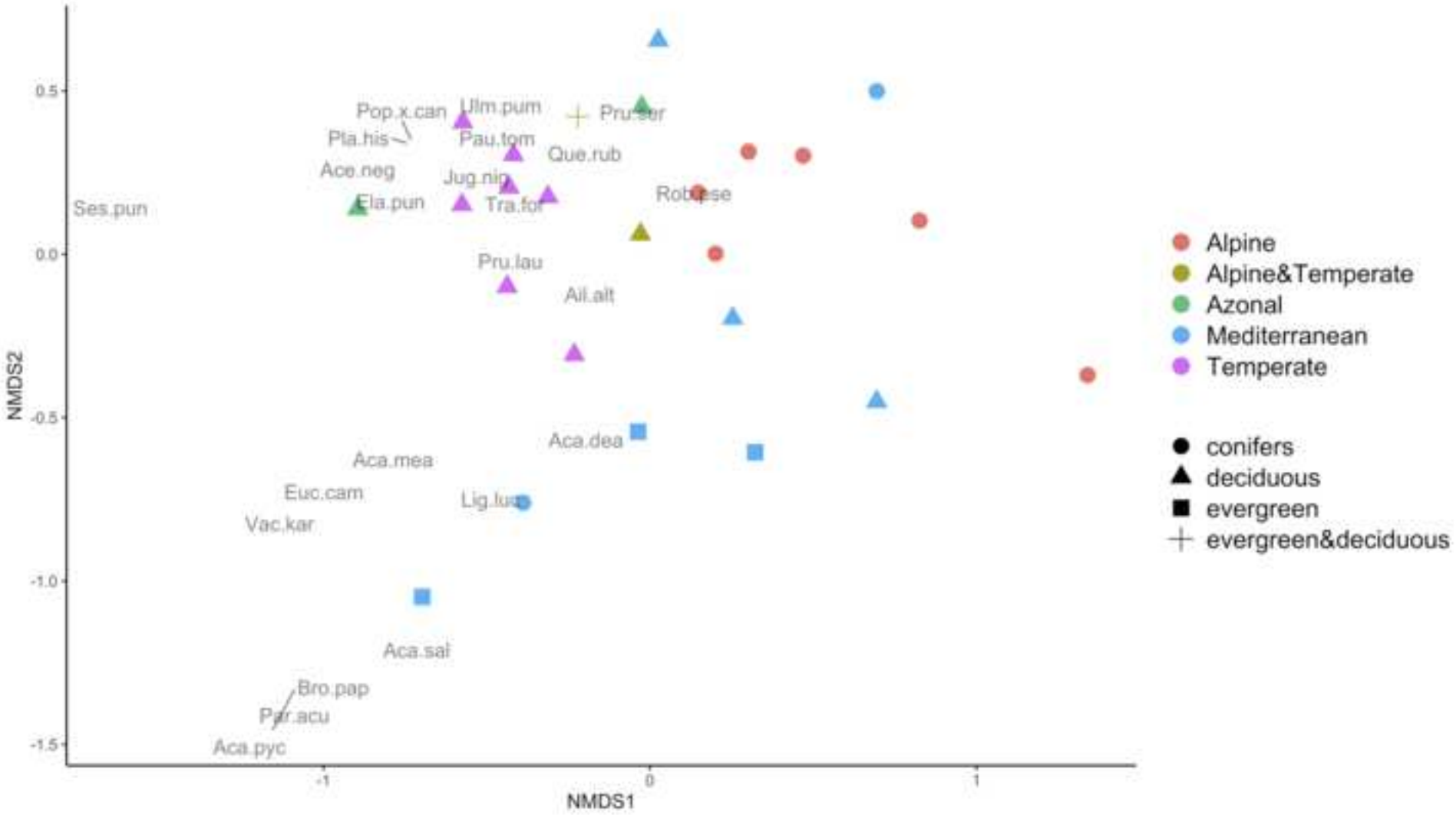


Figure 3

Click here to access/download;Figure;Fig3.tiff



Tree invasions in Italian forests

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Tree invasions in Italian forests

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Explanation of the spreadsheets in this excel file

"Matrix - invasion level"	We report the values
"References"	List of the full references

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Forest Category	Non-native tree species		
	Acacia dealbata		*Acacia mearnsi*
	Scale value	Reference	Scale value
Subalpine and temperate scrublands (heathlands)	0		0
Maquis, Mediterranean scrublands	2	Lazzaro et al. (2014), Lazzaro et al. (2020)	2
Mediterranean pine forests	1	Rodriguez et al. (2017)	0

Oak-hornbeam and hornbeam forests	0		0
Holm oak forests	2	Lazzaro et al. (2014), Lazzaro et al. (2020)	0
Cork oak forests	1	Lorenzo et al. (2013)	1
Downy oak forests	2	Lazzaro et al. (2020)	0
Sessile oak forests	0		0
Pedunculate oak forests	1	González-	0

Turkey oak forests	0		0
Other oak forests	0		0
Chestnut forests	1	González-	0
European ash-hornbeam forests	0		0
Maple-European ash and Maple-Lime forests	0		0
Pioneer forests	0		0
European beech forests	0		0
Mugo pine forests	0		0

Black pine forests	0		0
Scots pine forests	0		0
Silver fir forests	0		0
Norway spruce forests	0		0
Larch, Larch-Swiss pine and Swiss pine forests	0		0
Riparian forests	0		2
Forests dominated by sporadic conifers	0		0
Forests dominated by sporadic broadleaves	0		0
Urban forests	p		a

Total assigned to 1	4		1
Total assigned to 2	3		2
Total assigned to 3	0		0

ii	*Acacia provincialis*		*Acacia pycnantha*		*Acacia saligna*
Reference	**Scale value**	**Reference**	**Scale value**	**Reference**	**Scale value**
	0		0		0
Brundu G. (personal observation)	0		2	Lazzaro et al. (2015), Lazzaro et al. (2020)	3
	0		0		3

	0		0		0
	0		0		0
Boudiaf et al. (2013)	0		0		0
	0		0		0
	0		0		0
	0		0		0

	0		0		0
	0		0		0
	0		0		0
	0		0		0
	0		0		0
	0		0		0
	0		0		0
	0		0		0

	0		0		0
	0		0		0
	0		0		0
	0		0		0
	0		0		0
Brundu et al.	0		0		0
	0		0		0
	0		0		0
	a		a		d

	0		0		0
	0		1		0
	0		0		2

	Acer negundo		*Ailanthus altissima*		*Broussonetia p*
Reference	**Scale value**	**Reference**	**Scale value**	**Reference**	**Scale value**
	0		2	Gruppo di Lavoro Specie Esotiche della Regione Piemonte (2013a), Lazzaro et al. (2020)	0
Biondi et al. (2009), Del Vecchio et al. (2013), Iamonico et al. (2014), Lazzaro et al. (2020)	0		2	Lazzaro et al. (2020)	2
Biondi et al. (2009), Del Vecchio et al. (2013), Bonari et al. (2017), Badalamenti et al. (2018a), Lazzaro et al. (2020)	0		3	Badalamenti et al. (2012), Angelini et al. (2016), Lazzaro et al. (2020)	0

	2	Gruppo di Lavoro Specie Esotiche della Regione Piemonte (2014a)	3	Ebone et al. (2011), Angelucci (2011), Gruppo di Lavoro Specie Esotiche della Regione Piemonte (2013a), Lazzaro et al. (2020)	0
	0		2	Badalamenti et al. (2012)	0
	0		2	Badalamenti et al. (2012)	0
	0		3	Allegrezza et al. (2006), Biondi et al. (2009), Badalamenti et al. (2012), Lazzaro et al. (2020)	0
	2	Gruppo di	3	Biondi et al.	0
	2	Gruppo di	2	Del Favero	0

	0		2	Badalamenti et al. (2012)	0
	0		1	Dinucă (2021)	0
	2	Gruppo di	3	Badalamenti	0
	0		2	Radtke et al. (2013)	0
	2	Gruppo di Lavoro Specie Esotiche della Regione Piemonte (2014a)	2	Gruppo di Lavoro Specie Esotiche della Regione Piemonte (2013a), Angelini et al. (2016)	0
	0		0		0
	0		2	Badalamenti et al. (2012)	0
	0		0		0

	0		2	Badalamenti	0
	0		1	Motard et al.	0
	0		0		0
	0		0		0
	0		0		0
	3	Banfi and	3	Badalamenti	0
	0		0		0
	0		2	Badalamenti	0
	d	Sitzia et al.	d	Celesti-	d

	0		2		0
	5		11		1
	1		6		0

apyrifera	*Elaeagnus pungens*		*Eucalyptus camaldulensis*		*Juglans nigra*
Reference	**Scale value**	**Reference**	**Scale value**	**Reference**	**Scale value**
	0		0		0
Lazzaro et al. (2020)	0		2	Guarino et al. (2021)	0
	0		2	Biondi et al. (2009)	0

	0		0		2
	0		0		0
	0		0		0
	0		0		2
	0		0		0
	0		0		1

	0		0		0
	0		0		0
	2	Antonietti and	0		0
	0		0		0
	0		0		1
	0		0		1
	0		0		0
	0		0		0

	0		0		0
	0		0		0
	0		0		0
	0		0		0
	0		0		0
	0		2	Badalamenti	1
	0		0		0
	0		0		0
Scuderi and	p		p		p

	0		0		4
	1		3		2
	0		0		0

	Ligustrum lucidum		*Parkinsonia aculeata*		*Paulownia tom*
Reference	**Scale value**	**Reference**	**Scale value**	**Reference**	**Scale value**
	0		0		2
	2	Lazzaro et al. (2020)	2	Angelini et al. (2016)	0
	2	Galasso et al. (2016), Lazzaro et al. (2020)	0		0

Scatamacchia (2011)	0		0		2
	2	Prosser and Bertolli (2015), Lazzaro et al. (2020)	0		0
	0		0		0
Cicinelli et al. (2018)	0		0		0
	0		0		1
Šebesta et al.	0		0		1

	0		0		0
	0		0		0
	0		0		2
	2	Prosser and Bertolli (2015)	0		0
Šebesta et al. (2021)	0		0		2
Šebesta et al. (2021)	0		0		0
	0		0		1
	0		0		0

	0		0		0
	0		0		0
	0		0		0
	0		0		0
	0		0		0
Šebesta et al.	2	Lastrucci et al.	0		2
	0		0		0
	0		0		0
	p		d	Scuderi and	p

	0		0		3
	5		1		5
	0		0		0

ıentosa	*Platanus hispanica*		*Populus x canadensis*		*Prunus laurocer*
Reference	**Scale value**	**Reference**	**Scale value**	**Reference**	**Scale value**
Gruppo di Lavoro Specie Esotiche della Regione Piemonte (2020)	0		0		0
	0		0		2
	0		0		0

Gruppo di Lavoro Specie Esotiche della Regione Piemonte (2020)	2	Del Favero (2002), Mason (2004)	1	Šebesta et al. (2021)	1
	0		0		0
	0		0		0
	0		0		1
Maringer et al.	2	Del Favero	0		1
Maringer et al.	2	Del Favero	1	Šebesta et al.	1

	0		0		0
	0		0		0
Gruppo di	0		0		2
	0		0		1
Gruppo di Lavoro Specie Esotiche della Regione Piemonte (2020)	2	Del Favero (2002)	1	Šebesta et al. (2021)	1
	0		1	Šebesta et al. (2021)	0
Maringer et al. (2012)	0		0		1
	0		0		0

	0		0		0
	0		0		0
	0		0		1
	0		0		0
	0		0		0
Gruppo di	2	Del Favero	2	Cicinelli et al.	2
	0		0		0
	0		0		0
Essl (2007),	p		p		p

	0		4		8
	5		1		3
	0		0		0

rasus	*Prunus serotina*		*Quercus rubra*		*Robinia pseudo*
Reference	**Scale value**	**Reference**	**Scale value**	**Reference**	**Scale value**
	2	Gruppo di Lavoro Specie Esotiche della Regione Piemonte (2013b)	2	Biondi et al. (2009), Gruppo di Lavoro Specie Esotiche della Regione Piemonte (2013c)	3
Lucchese (2017)	0		0		0
	0		0		2

Hättenschwiler and Körner (2003)	3	Del Favero (2002), Biondi et al. (2009), Angelucci (2011), Gruppo di Lavoro Specie Esotiche della Regione Piemonte (2013b), Terwei et al. (2013), Angelini et al. (2016), Lazzaro et al. (2020)	3	Biondi et al. (2009), Gruppo di Lavoro Specie Esotiche della Regione Piemonte (2014b), Prosser and Bertolli (2015), Lazzaro et al. (2020)	3
	0		0		2
	0		0		0
Conedera et al. (2018)	0		2	Lazzaro et al. (2020)	3
Conedera et	2	Del Favero	3	Del Favero	3
Descombes et	3	Del Favero	3	Del Favero	3

	2	Annighöfer et al. (2012)	2	Annighöfer et al. (2012), Lazzaro et al. (2020)	0
	0		0		0
Antonietti and	2	Del Favero	2	Del Favero	3
Fehr and Burga (2016)	0		0		3
Conedera et al. (2018)	0		2	Gruppo di Lavoro Specie Esotiche della Regione Piemonte (2013c)	3
	1	Vanhellemont (2009)	1	Major et al. (2013), Wagner et al. (2017)	2
Rusterholz et al. (2018)	1	Maringer et al. (2012)	1	Wagner et al. (2017), Medvecká et al. (2018), Bindewald et al. (2021)	2
	0		0		0

	1	Godefroid et	0		2
	2	Del Favero	1	Halarewicz	2
Wagner et al.	0		1	Wagner et al.	0
	1	Starfinger et	1	Wagner et al.	2
	1	Vanhellemont	0		2
Gruppo di	3	Gruppo di	2	Gruppo di	3
	0		0		2
	0		0		2
Sitzia et al.	p		p		d

	5		5		0
	5		6		10
	3		3		9

pacacia	*Robinia viscosa*		*Sesbania punicea*		*Ulmus pumila*
Reference	**Scale value**	**Reference**	**Scale value**	**Reference**	**Scale value**
Biondi et al. (2009), Gruppo di Lavoro Specie Esotiche della Regione Piemonte (2014b), Prosser and Bertolli (2015), Lazzaro et al. (2020)	0		0		0
	0		0		0
Angelini et al . (2016)	0		0		0

Angeles-Gras (1991; as cited in Sitzia 2009), Del Favero (2002), Angelucci (2011), Gruppo di Lavoro Specie Esotiche della Regione Piemonte (2014b), Prosser and Bertolli (2015), Angelini et al. (2016), Lazzaro et al. (2020)	0		0		0
Lazzaro et al. (2020)	0		0		0
	0		0		0
Del Favero (2002), Sitzia (2009), Prosser and Betolli (2015), Angelini et al. (2016), Lazzaro et al. (2020)	0		0		0
Angeles-Gras	0		0		0
Del Favero	0		0		0

	0		0		0
	0		0		0
Del Favero	0		0		0
Del Favero (2002), Del Favero (2004), Sitzia (2009), Odasso et al. (2018)	0		0		0
Del Favero (2002), Sitzia (2009), Gruppo di Lavoro Specie Esotiche della Regione Piemonte (2014b), Prosser and Betolli (2015), Angelini et al. (2016), Lazzaro et al. (2020)	0		0		0
Sitzia (2009), Sitzia et al. (2012)	0		0		3
Prosser and Betolli (2015), Angelini et al. (2016), Lazzaro et al. (2020)	0		0		0
	0		0		0

Sitzia (2009)	0		0		0
Del Favero	0		0		0
	0		0		0
Campagnaro	0		0		0
Sitzia (2009)	0		0		0
Del Favero	0		2	Brunel et al.	3
Lazzaro et al.	0		0		0
Biondi et al.	0		0		0
Sitzia et al.	a		0		p

	0		0		0
	0		1		0
	0		0		2

	Trachycarpus fortunei		*Vachellia karroo*	
Reference	**Scale value**	**Reference**	**Scale value**	**Reference**
	0		0	
	0		2	Biondi et al. (2009), Angelini et al. (2016), Lazzaro et al. (2020)
	0		2	Biondi et al. (2009), Gioia (2021)

	2	Lazzaro et al. (2020)	0	
	0		0	
	0		0	
	2	Fehr and Burga (2016)	0	
	2	Fehr and Burga	0	
	1	Conedera et al.	0	

	0		0	
	0		0	
	2	Fehr and Burga	0	
	2	Fehr and Burga (2016)	0	
	2	Fehr and Burga (2016), Lazzaro et al. (2020)	0	
Brunet et al. (2013), Prosser and Bertolli (2015), Mainetti and Lonati (2017)	2	Fehr and Burga (2016)	0	
	1	Maringer et al. (2012)	0	
	0		0	

	0		0	
	0		0	
	0		0	
	0		0	
	0		0	
Prosser and	2	Bona and Federici	2	La Mantia T.
	0		0	
	0		0	
Maineti and	p	Sitzia et al. (2016)	d	

	2		0
	8		3
	0		0

Total assigned to 1	Total assigned to 2	Total assigned to 3
0	4	1
0	10	1
1	4	2

2	5	4
0	4	0
2	1	0
1	4	2
2	4	3
6	3	3

0	3	0
1	0	0
1	7	2
1	3	1
3	6	1
4	2	1
5	2	0
0	0	0

1	2	0
2	2	0
2	0	0
2	1	0
1	1	0
1	11	5
0	1	0
0	2	0

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Tree invasions in Italian forests

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Supplementary Information 2

Table SI2: Status (CAS: casual, NAT: naturalized, INV: invasive) of the selected 24 non-native tree species in 2009, 2018, and 2021. Numbers indicate the number of regions with such status in Italy.

Invasive non-native tree	Celesti-Grapow et al. 2009			**Total (2009)**	Galasso et al. 2018			**Total (2018)**	Acta Plantarum 2021			**Total (2021)**
	CAS	NAT	INV		CAS	NAT	INV		CAS	NAT	INV	
Acacia dealbata subsp. *dealbata*	5	1	2	**8**	5	2	2	**9**	5	3	2	**10**
Acacia mearnsii	0	0	1	**1**	0	0	1	**1**	0	0	1	**1**
Acacia provincialis	0	0	1	**1**	1	1	1	**3**	2	1	1	**4**

Acacia pycnantha	2	0	0	**2**	0	1	1	**2**	0	1	1	**2**
Acacia saligna	2	4	3	**9**	2	3	5	**10**	2	3	5	**10**
Acer negundo	7	6	4	**17**	7	6	6	**19**	7	6	6	**19**
Ailanthus altissima	0	0	20	**20**	0	0	20	**20**	0	0	20	**20**
Broussonetia papyrifera	5	10	3	**18**	4	10	4	**18**	5	10	4	**19**
Elaeagnus pungens	2	2	0	**4**	6	3	1	**10**	6	2	2	**10**
Eucalyptus camaldulensis subsp. *camaldulensis*	7	2	0	**9**	5	5	1	**11**	5	5	1	**11**
Juglans nigra	6	0	0	**6**	7	1	1	**9**	8	2	1	**11**
Ligustrum lucidum	7	9	0	**16**	5	10	2	**17**	5	10	2	**17**
Parkinsonia aculeata	2	0	1	**3**	4	1	1	**6**	3	1	2	**6**
Paulownia tomentosa	5	5	0	**10**	8	6	1	**15**	10	6	1	**17**
Platanus hispanica	8	8	0	**16**	7	10	0	**17**	7	10	1	**18**

Populus ×canadensis	12	5	0	**17**	10	8	0	**18**	9	7	2	**18**
Prunus laurocerasus	9	1	1	**11**	10	1	3	**14**	11	1	4	**16**
Prunus serotina	2	0	3	**5**	3	1	3	**7**	3	1	3	**7**
Quercus rubra	4	1	2	**7**	5	2	2	**9**	7	2	2	**11**
Robinia pseudoacacia	0	3	17	**20**	0	3	17	**20**	0	3	17	**20**
Robinia viscosa	1	0	0	**1**	0	0	1	**1**	0	0	1	**1**
Sesbania punicea	1	0	0	**1**	3	2	0	**5**	2	1	2	**5**
Trachycarpus fortunei	3	1	2	**6**	5	2	3	**10**	7	2	3	**12**
Ulmus pumila	5	2	0	**7**	3	5	2	**10**	3	7	2	**12**
Vachellia karroo (= *Acacia karroo*)	0	4	0	**4**	2	5	0	**7**	2	4	1	**7**
	94	64	60	**218**	99	86	78	**263**	108	88	81	**277**

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