Urban Forestry & Urban Greening 105 (2025) 128674

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Original article

Collaborative approaches to urban tree biosecurity: Stakeholder's perceptions, actions and social networks

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A R T I C L E I N F O

Keywords:
Alien invasive species
Biological invasions

A B S T R A C T

In past decades, urban tree biosecurity has taken on growing importance worldwide. Stakeholders play a key role in countering the spread of invasive alien pests and pathogens that affect the health of urban green

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https://doi.org/10.1016/j.ufug.2025.128674
Received 19 July 2024; Received in revised form 22 October 2024; Accepted 10 January 2025
Available online 16 January 2025

Biosecurity awareness
Social network analysis
Urban tree resilience
Urban tree health

infrastructures. The aim of this study was to increase the understanding of the role of stakeholders' perceptions, priorities and networks in the implementation of actions to guarantee a coherent biosecure system. The research was done in three steps. First, stakeholder mapping was carried out to identify relevant actors. Second, a questionnaire on perceptions, actions and collaboration among stakeholders involved in urban biosecurity was developed and administered. Third, data was processed to compare the responses given by the different categories of stakeholders. Stakeholder mapping identified 953 relevant stakeholders of which 255 stakeholders from 19 countries completed the online survey. According to the stakeholders, the current most important urban tree pests across Europe are *Cameraria ohridella* and *Cydalima perspectalis*, mentioned in 13 and 12 countries respectively, while other pests and pathogens have been specifically mentioned in individual countries (*Thaumetopoea pityocampa* in Spain, *Ips typographus* in Latvia and Serbia, *Ceratocystis platani* in Italy and Türkiye). Regarding future threats to urban trees, the stakeholders emphasised significant concerns around the bacterial plant pathogen *Xylella fastidiosa* and insect pest *Agrilus planipennis*, mentioned in 12 and 14 countries respectively. In addition, the outcome of the study highlighted that the most widely adopted biosecurity actions by stakeholders are those related to communication, both to the general public (information) and to the staff involved in the biosecurity sector (training). A network analysis of relationships between stakeholder groups evidenced positive collaborations that tended to be more common the closer to hands-on practice of tree care the stakeholders were. The study provided a snapshot of the European stakeholders' perceptions and readiness to implement biosecurity actions, highlighting the importance of connectedness as the basis to guarantee a coherent biosecure system.

1. Introduction

It has been estimated that the percentage of the European population living in urban areas will grow to over 84 % by 2050 (United Nations, 2019). In the European Union (EU) countries, currently about 75 % of the population live in urban areas, mainly in big cities with more than 50,000 inhabitants but also in towns and suburbs with more than 5000 inhabitants (Lavalle et al., 2017). In a context of growing urbanisation, the urban green infrastructures (UGI) – defined as the network of green areas within the urban environment (Hanna et al., 2023) – play a key role in the physical and mental well-being of European citizens (McKinney and VerBerkmoes, 2020; Reyes-Riveros et al., 2021). The benefits provided by UGI include carbon sequestration, water regulation, cooling effects, biodiversity conservation, and air and noise pollution mitigation (Anderson and Gough, 2020; Evans et al., 2022; Iungman et al., 2023; Shadman et al., 2022). The European Commission has incorporated the improvement of UGI in the list of strategies aimed to increase the capacity of urban environments to climate adaptation and sustainable development (Hanna et al., 2023).

Invasive alien pests and pathogens (IAPPs) that spread by natural (e.g., wind, rain, or native insects) or by anthropogenic pathways (e.g., transportation of plants or plant parts, hitchhiking on human) (Liebhold et al., 2012; Santini et al., 2013) represent a growing threat to urban trees that constitute a critical element in UGI (Padayachee et al., 2017; Paap et al., 2017; Roman et al., 2021; Zlatkovic et al., 2016). The impact of IAPPs has increased mainly due to global trade and transport in recent years as a result of increased rate of IAPP introductions to new areas (Ghelardini et al., 2022; Sutcliffe et al., 2018; Zlatkovic et al., 2019). In addition, environmental conditions altered by climate change facilitate the establishment and spread of IAPPs either by directly influencing their growth and reproduction or indirectly by altering the physiology and biochemistry of their plant hosts (Novoa et al., 2017; Padayachee et al., 2017; Ramsfield et al., 2016; Roman et al., 2021). The current plant biosecurity system – consisting of a set of measures to prevent the introduction and spread of IAPPs and to reduce their impact on the environment (Paap et al., 2017; Sutcliffe et al., 2018) – has shown to be inefficient and error-prone (Santini et al., 2023; Vettraino and Santini, 2021). In fact, the risk of tree pest and pathogen invasions is considered to be increasing, posing a particular vulnerability to UGI (Nahrung et al., 2023), due mainly to the presence of densely planted mixtures of native and non-native trees that allow for evolutionary "host jumps" of insects and pathogens. In addition, various plant stress factors (e.g., soil compaction, salt exposure, "heat island effect") multiply IAPPs impact by favouring their development (Raum et al., 2023). Moreover, the biosecurity context in urban areas is complex due to multiple stakeholders with different responsibility for tree management, interests and influence. This can lead to conflicts between different categories of stakeholders, necessitating implementation of processes that seek to understand the different perspectives (Kirkpatrick et al., 2013; Novoa et al., 2017).

There is evidence to suggest that communication and stakeholder involvement are crucial for the success of both prevention and mitigation of introduction, spread and establishment of IAPPs (Marzano et al., 2015). Several recent studies have focused on the stakeholders involved in tree biosecurity. Some of them focused on stakeholder mapping and analysis, in order to identify, categorise or analyse the multitude of categories, as explored by Dandy et al. (2013) and Reed and Curzon (2015) for biosecurity governance. Other contributions deepened the process of stakeholders' engagement in the management of IAPPs by using different approaches (e.g., facilitated workshop, consultation process) with the aim of integrating different knowledge and perspectives in the management of invasive species (Novoa et al., 2018; Shackleton et al., 2019). Particular attention has been given to the involvement of the public in citizen science campaigns in the detection of tree pests and pathogens in urban green areas, especially for the thorough knowledge that the inhabitants usually have of the local territory (Gupta et al., 2022). Another topic of interest is the social perception of tree pest and pathogen outbreaks and the acceptability of tree health management methods for different categories of stakeholders (Kirkpatrick et al., 2013; Marzano et al., 2021; Sutcliffe et al., 2018). Special attention is paid to risk perceptions amongst the general public (Fuller et al., 2016; Gutsch et al., 2019; Urquhart et al., 2017b), who are rarely involved in biosecurity activities except for citizen science initiatives but have a strong influence on decision-making around socially acceptable approaches. Issues around public responses to management of ash dieback and Asian long-horned beetle as well as ethical considerations informing reporting behaviours have been explored (Dandy et al., 2013; Marzano et al., 2020; Pocock et al., 2017). Other studies have focused on stakeholder awareness and knowledge, which represent key components in the elaboration of effective actions against tree pests and pathogens (Marzano et al., 2016). For example, Sallmannshofer et al. (2023) assessed forest managers' awareness of both abiotic and biotic environmental changes in the UNESCO protected Biosphere Reserve including IAPPs. Moreover, it is recognized that a more complete understanding of all factors that influence the actions and decisions of stakeholders is needed to improve existing collaborations, create new ones, and develop effective attempts to improve biosecurity policies and practices (Marzano et al., 2017). An aspect of biosecurity that often remains poorly explored and understood is the importance of social networks. A social network is a structure that consists of nodes (i.

e., stakeholder categories) and ties (i.e., relationships among stakeholder categories). Social Network Analysis is an effective tool to analyse the ties in a multiple actors and interests context (Harshaw and Tindall, 2005) with the aim of improving collective action, something which is essential in urban biosecurity (Prell et al., 2009).

In this study, the main objective was to examine the perspectives of a broad range of stakeholders across Europe to better understand the social dimension of urban tree biosecurity and to propose strategies for improving interactions among these groups. In particular, the investigation was divided into four sub-objectives:

1. Understand if all relevant parties are engaged in implementing biosecurity strategies in European countries. To achieve this stakeholder groups involved in urban tree biosecurity have been identified and characterized.
2. Identify whether knowledge of current and future risks to biosecurity in European urban forests varies between stakeholder groups.
3. Explore stakeholders' involvement in prevention, management and monitoring actions.
4. Identify key social networks among stakeholders in order to assess where actions within the urban biosecurity system may be particularly necessary to improve communication or collaboration.

This study was conducted as part of the activities in COST Action CA20132 "Urban Tree Guard - Safeguarding European urban trees and forests through improved biosecurity (UB3Guard)" (https://ub3guard.eu/).

2. Materials and methods

The study design is based on grounded theory taking into account previous literature concerning stakeholder analysis and social network analysis in natural resource management (Prell et al., 2009; Paletto et al., 2015; Bendtsen et al., 2021). As emphasized by Hardy (2005), grounded theory is suitable for assessing the human dimension and social setting based on systematic collection of data. In this study, grounded theory approach was adopted by integrating the data collected through the questionnaire with a summary of the literature on the topic, validated by a panel of experts. Therefore, an interactive process of constant comparison between the different stakeholders' views on emerging issues was adopted (Creswell, 1998). To this end, the following four steps have been implemented.

2.1. Identification and description of stakeholder groups

In the first step, the authors identified key stakeholders related to the monitoring and management of IAPPs in the urban areas of their country through a stakeholder mapping exercise. A stakeholder analysis considered the "interest" and "influence" of stakeholders on an outbreak of urban tree pests and pathogens (Dandy et al., 2013; Reed and Curzon, 2015). The definition of stakeholder adopted was "an individual or organisation which can either affect or be affected by a tree outbreak" (Dandy et al., 2013, p.3). Based on this definition, a variety of stakeholders can be considered part of the biosecurity issues such as general public, academic experts, governmental bodies, and non-governmental organisations (Friedman and Miles, 2006; Novoa et al., 2017; Wesselink et al., 2011). However, the stakeholder mapping for the study's objectives focused on organisations and groups (e.g., public administrations, private organisations, third sector associations), while individuals (i.e., single citizens) were excluded. In particular, the seven categories of stakeholders have been prepared starting from the results of Dandy et al. (2013) and Marzano et al. (2017) who classified the stakeholders considering a set of stakes in tree pest outbreaks and the specific capabilities, behaviours and practices of groups. Those authors identified five stakeholder categories (Dandy et al., 2013): governors (responsible for the preparation and implementation the rules and regulations on urban tree biosecurity); vectors (responsible for the physical movement of pests and diseases within the supply chains); controllers (those who have the skills and resources to control or manage of pests or pathogens outbreaks); monitors (those who have the knowledge and information to detect, identify and predict pests or pathogens); networkers (those who can affect pests and pathogens outbreaks through knowledge exchange and communication). In the present study, the five categories provided by Dandy et al. (2013) have been re-categorized into seven categories to facilitate the identification of stakeholders in all the countries involved. The key players in the physical movement of pests and diseases (i.e. vectors) within the supply chains were divided into those who supply (Suppliers), purchase (Consumers), resell (Retailers), transport and store (Transport Storage). From these four categories, the Site Vectors were distinguished, those who can move soil and plant material within and between sites such as machine-hire companies, recreationists and arborists. The category of Policy regulation includes rule setters (i.e. governors), while the category of Advice and Influence includes all those who provide consultancy and apply specialist knowledge in control, management and monitoring of pests and pathogens.

Based on the theoretical assumptions of the stakeholder analysis, a preliminary list of stakeholders, who can be considered part of the biosecurity issues, was prepared on the basis of a literature review on the topic. The preliminary list of stakeholders has been validated by the core group of the COST Action UB3Guard, which includes expert forest entomologists, pathologists and social scientists. At the end of the validation process, seven categories and twenty-nine subcategories of stakeholders were identified, as shown in Table 1. Afterwards, the COST Action UB3Guard participants from 19 countries (Bosnia and Herzegovina, Croatia, Estonia, Finland, Germany, Hungary, Iceland, Italy, Latvia, Lithuania, North Macedonia, Poland, Portugal, Serbia, Slovakia, Slovenia, Spain, Turkey, United Kingdom) identified the stakeholders for their country based on the categories and subcategories previously described. At the end of this step, 953 stakeholders were identified and classified by category and subcategory.

2.2. Assessment of the major threats and priority actions for urban trees

In the second step, a semi-structured questionnaire was administered online to the stakeholders identified during the stakeholder mapping via the country representatives involved in the COST Action UB3Guard. A preliminary version of the questionnaire was developed and pre-tested with five stakeholders. After the pre-test, the final version of the questionnaire was structured into four thematic sections. The first section focused on the respondents', namely: category of stakeholder, country of origin, role of respondents in their organisation/association, and territorial levels of action of the reference organisation. The second section focused on the pests and pathogens that threaten UGI. The respondents indicated for their context what they considered to be the most important pests or pathogens both currently and in the near future, specifying the main causes of spread for each of them. In the third section, the actions used for pest/pathogen management were explored. For this purpose, a list of 19 actions was drawn up, and respondents were asked to indicate for each one whether it is currently implemented by their organisation. The list of actions – distinguishing between prevention, management, and monitoring actions – was elaborated through a brainstorming session by urban pest and pathogen experts involved in UB3. The brainstorming session was organized in two groups, involving pests and pathogens experts respectively. Participants in the brainstorming session worked online to prepare the most comprehensive list of prevention, management, and monitoring actions based on their knowledge. In addition, they were supported by a facilitator from the COST Action UB3 core group in order to collect and synthesize ideas. The lists of actions prepared by the two groups were integrated and validated by the COST Action UB3 core groups. In the fourth section, collaboration between categories of stakeholders was analysed. To this

Table 1
Distribution of the identified stakeholders and respondents by category.

Code	Category		Stakeholders	
			Identified	Respondents
A0	Suppliers	- Forestry and horticultural growers - Suppliers of soil, bark and compost	109	29
B0	Retailers	- Garden centres, online retailers, non-specialist retailers - Nurseries - Wholesalers	96	10
C0	Consumers	- Local/regional/national authorities - Protected area managers - Botanical gardens managers - Public forest and garden managers - Land managers, landscaping professionals, facilities management - Plant managers for infrastructure and buildings - Charity/non-governmental organisations for natural conservation - Private companies - General public	150	44
D0	Transport Storage	- Border and custom authorities - Transporters/logistics - Importers/exporters	37	3
E0	Site Vectors	- Machine hire companies - Recreationists/tourists - Arborists/ tree technician/ tree workers	85	15
F0	Policy Regulation	- Government agencies - Non-ministerial public bodies	113	35
G0	Advice Influence	- Consultants for retailers, forestry consultants, business decision makers - Education and training providers - Garden designers, landscape architects - Local authority tree officers - Scientific researchers - Associations/ consortiums/ special interest groups - Citizen scientists - Plant health inspectors	348	119
Others			15	0
TOTAL			**953**	**255**

end, the respondents indicated which other categories of stakeholders they collaborated with in urban tree biosecurity, specifying the strength (strong or weak) of the collaboration.

The final version of the questionnaire was translated into 14 different languages – Bosnian, Croatian, Czech, English, Hungarian, Italian, Lithuanian, Macedonian, Polish, Serbian, Slovenian, Spanish, Swedish and Turkish – to reach a broad range of stakeholders across the involved countries. Finally, the questionnaire was sent by email to all stakeholders identified in the stakeholder mapping. The link to the questionnaire prepared with Google Forms was introduced by a short explanatory text of the study and its objectives.

The sample of respondents to the questionnaire was 26.8 % of the total stakeholders identified in the 19 countries involved in the survey. However, the sample was characterized by a significant difference between the identified stakeholders and those who responded to the questionnaire due to the different situations in each country. Some countries identified few stakeholders during the step of mapping and achieved high response rates (e.g., in Slovakia, North Macedonia, and Lithuania, 16, 21, and 18 stakeholders were identified and response rates of 75.0 %. 47.6 %, and 44.4 % were obtained respectively). Conversely, other countries identified a high number of stakeholders, but achieved low response rates (e.g., in Finland and Latvia, 36 and 81 stakeholders were identified and non-response rates of 8.3 % and 7.4 % were obtained respectively). Therefore, the sample of respondents cannot be considered representative in all the countries involved in the survey, but it was useful to provide an overall overview at European level.

2.3. Data processing

The data processing was carried out considering the different categories of stakeholders identified in the stakeholder mapping. First, the data was analysed according to the different characteristics of the respondents and descriptive statistics were produced. A list of the 134 current and 126 future most important pests or pathogens considered as threats to urban trees was created using the data of the second section. The pests and pathogens mentioned by respondents were ranked according to Eq. (1):

$$I_i = (N1_i \bullet W1_i) + (N2_i \bullet W1_i) + (N3_i \bullet W3_i) \quad (1)$$

Where:

I_i = aggregate index of importance for the pest/pathogen species i;

$N1_i$ = number of respondents who indicated species i as the first threat;

$N2_i$ = number of respondents who indicated species i as the second threat;

$N3_i$ = number of respondents who indicated species i as the third threat;

$W1_i$ = weight assigned to the first threat;

$W2_i$ = weight assigned to the second threat;

$W3_i$ = weight assigned to the third threat.

Based on the results of the third section, the most adopted actions for urban tree pest/pathogen management were identified and analysed by category of stakeholders.

2.4. Mapping the collaboration networks between stakeholders

Finally, a social network analysis (SNA) was applied based on the outcomes of the fourth section. Cooperation between categories of stakeholders were analysed considering only positive interactions and strong and weak ties (i.e., from +1 weak positive interaction to +2 very strong positive interaction). In order to highlight positive collaborations in the implementation of urban biosecurity actions, conflicting relationships are not shown in this article, although they were collected in the questionnaire responses. Seven directed networks about positive collaboration between stakeholders were analysed, distinguishing by stakeholder category (i.e., suppliers, retailers, consumers, transport storage, site vectors, policy regulators and advice influence). The strength of the tie was used to weigh the importance of collaboration, considering that a strong tie tends to influence another stakeholder more than weak tie due to a sharing of similar points of view (Coleman, 1990). The sociograms – graphic representations of the links between stakeholders – were developed considering all the countries together and not individually.

The role of each category in the network was analysed using two indicators: Degree Centrality (*Dc*) and Betweenness Centrality (*Bc*). According to Freeman (1979), *Dc* can be defined as the number of links (collaboration ties) occurred upon a node (stakeholder). *Dc* is the most widely adopted measure of centrality and it represents the measure of the social status, power and prestige of a stakeholder in a network. Freeman's formula for *Dc* (Freeman, 1979) is applied to this study (Eq. (2)):

$$Dc(n_i) = \sum_{k=1}^{n} a_{ik}(n_i, n_k)(N-1)^{-1} \quad (2)$$

Where:
Dc = Degree centrality
a_{ik} = arc between nodes (1 when there is a connection between n_i and n_k; 0 when there is no connection between n_i and n_k)

Freeman's *Bc* is the ratio of the shortest path between two nodes to the sum of all such shortest paths (Freeman, 1977). This indicator is the measure of the influence that a category of stakeholders has over the spread of information through the entire network. Therefore, it highlights those stakeholders who play an intermediary role in the decision-making process (Newman, 2005). *Bc* was calculated using the following formula (Freeman, 1979) (Eq. (3)):

$$Bc(n_i) = \sum_{j}^{N} \sum_{k}^{N-1} \frac{D_{jk}(n_i)}{D_{jk}} \quad (3)$$

Where:
Bc = Betweenness centrality;
D_{jk} = set of minimum paths connecting the node n_j with the node n_k;
$D_{jk}(n_i)$ = set of minimum paths connecting the node n_j with the node n_k through the node n_i.

The indicators and the graphic elaborations of the SNA were processed through the UCINET 6.504 software (Borgatti et al., 2002).

3. Results

3.1. Identification and description of stakeholder groups

The 953 stakeholders identified in the 19 countries who participated in the survey were classified into seven categories, as shown in Table 1. The majority of the identified stakeholders fell into the category of Advice Influence (36.5 %), followed by Consumers (15.7 %), and Policy and Regulation (11.9 %).

After the identification of stakeholders and emailing the questionnaire to them by country representatives, 255 stakeholders participated in the survey (Table 1). Of these, the majority belonged to the category of Advice Influence; the categories Consumers, Policy and Regulations, and Suppliers were also well represented. More than half of the respondents came from six countries: Italy (17.0 %), Poland (13.0 %), Portugal (8.7 %), United Kingdom (7.1 %), Hungary (5.9 %), and Serbia (5.9 %).

Over 32 % of the respondents were public sector employees (28.0 %) or private sector employees (4.3 %), while 22.1 % of respondents had a managerial role in their organisation (13.4 % as managers or 8.7 % as directors). In addition, the results highlighted that the majority of organisations operate at the national (32.9 %), regional (26.4 %), and municipality level (23.7 %), while only 13.1 % operate internationally (9.2 % and 3.9 % at EU and global level, respectively) and 3.9 % at local level.

3.2. Assessment of the major threats and priority actions for urban trees

Respondents identified 184 species as the most important pests and pathogens currently threatening UGI (Table S1). The most commonly identified cases included four insect pests (in descending order:

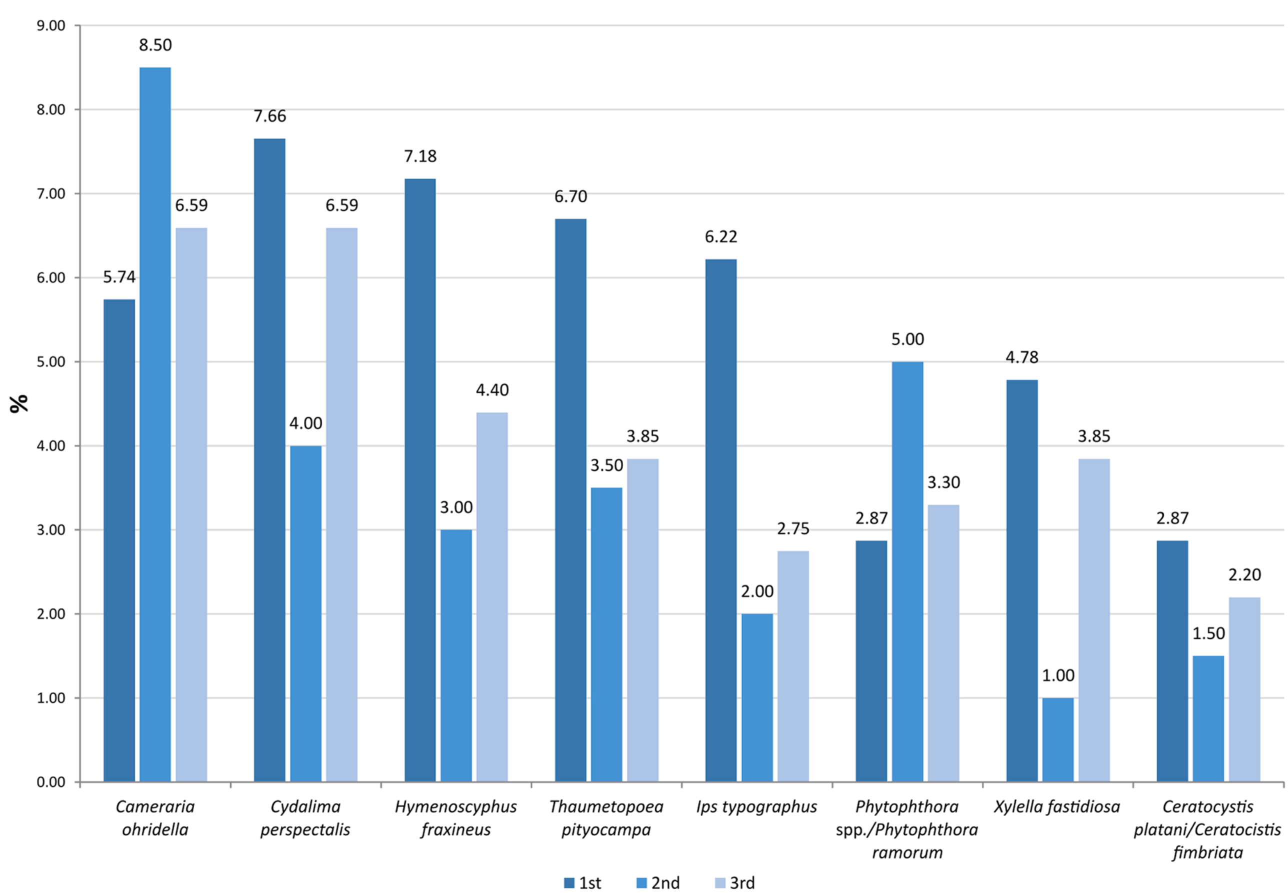

Fig. 1. The first, second, and third most significant current pests and pathogens in UGI, in accordance with the stakeholders' opinions (% on total answers).

Cameraria ohridella, *Cydalima perspectalis*, *Thaumetopoea pityocampa*, *Ips typographus*), two fungal pathogens (*Hymenoscyphus fraxineus*, *Ceratocystis platani*), one bacterial pathogen (*Xylella fastidiosa*) and pseudo-fungi belonging to Oomycetes (*Phytophthora* spp.) (Fig. 1, Suppl. Table 2). The highest aggregate index of importance values (I_i) were found for *C. ohridella* (I_i: 82, mentioned by 16.2 % of respondents n = 253), *C. perspectalis* (I_i: 76, mentioned by 14.2 % of respondents), and *H. fraxineus* (I_i: 65, mentioned by 11.5 % of respondents). Analysing the data by country, *C. ohridella* was the most important threat of urban trees in five Central-Eastern European countries (Croatia, Estonia, Hungary, Lithuania, and Slovakia), while *C. perspectalis* in three countries (Bosnia and Herzegovina, North Macedonia, and Poland). *Ceratocystis platani* was mentioned as the most important UGI threat by Italian and Turkish stakeholders, while *T. pityocampa* was considered a major UGI threat by most Spanish stakeholders. In addition, it is interesting to highlight that *X. fastidiosa* was mentioned by stakeholders from few countries (e.g. Italy and Portugal), while *I. typographus*, although mentioned by stakeholders in nine countries, was considered the main threat of UGI only in Latvia and Serbia. Icelandic stakeholders did not indicate any current threats to UGI.

The main pests and pathogens that respondents considered to be the most significant concern for the near future included: *X. fastidiosa*, *Phytophthora* spp., *C. perspectalis*, but also the wood-boring beetles *Agrilus planipennis*, *Anoplophora glabripennis*, and the foliage feeding scarab beetle *Popillia japonica* (Fig. 2, Table S2). The aggregate index values (I_i) were highest for *X. fastidiosa*, *A. planipennis*, and *Phytophthora* spp. (I_i: 63, 57, and 55, respectively; mentioned by 9.5, 9.5, and 9.1 % of the respondents). Analysing the data by country, stakeholders in six countries (Croatia, Estonia, Finland, Hungary, Lithuania, and Slovakia) considered *A. planipennis* as the main future threat of UGI, while the future importance of *A. glabripennis* was emphasised in three countries (Bosnia and Herzegovina, Germany, and Slovenia). *P. japonica* was indicated by stakeholders in six countries as a future threat but with particular importance in Germany, Italy, and Poland, while Serbian stakeholders emphasised the future importance of *C. perspectalis*, and Bosnian stakeholders that of *H. fraxineus* as threat of UGI. Furthermore, it is important to highlight that *X. fastidiosa* was listed as a future UGI threat in 12 countries including some that had not listed it as a current threat (Bosnia and Herzegovina, Croatia, Finland, Hungary, North Macedonia, Poland, Serbia, and Spain). Similarly, *Phytophthora* spp. was highlighted as a future UGI threat by stakeholders in 15 countries including countries that had not listed this species as a current threat (Croatia, Estonia, Iceland, Latvia, Lithuania, Slovakia).

Natural pathways (e.g., wind, native insects) and imported plant trade material were considered the most important ways of introduction of pests and pathogens, while visitors from other European or non-European countries and imported food products were considered the least relevant pathways. (Suppl. Table 3). Considering the individual pests and pathogens, the results showed that natural vectors are the most common ones for *C. ohridella* (for 57.7 % of respondents), *C. perspectalis* (44.3 %), *H. fraxineus* (54.9 %), *T. pityocampa* (66.7 %), *I. typographus* (75.0 %), *Phytophtora* spp. (31.1 %). Conversely, imported trees and plants is considered in accordance with the stakeholders' opinions the main pathway for *X. fastidiosa* (43.6 %) and *C. platani* (26.7 %).

Table 2
Actions to prevent or manage tree pests and pathogens in UGI.

Actions	Adopted
Prevention actions	
Staff training on tree/plant health (e.g., ID skills, legislation)	77.6 %
Regular visual inspections and laboratory analyses	68.1 %
Planting new trees or replacements made exclusively with certified plant material	66.5 %
Reliance on mains or treated water (e.g., antibacterial and antifungal treatment, anaerobic water treatment)	45.3 %
Regulated irrigation and drainage systems which prevent puddling on-site	39.0 %
Quarantining of new plants	39.0 %
Washing station for plant pots and tools	35.4 %
Boot washing station/disinfecting mat	28.0 %
Vehicle washing station	22.0 %
Management actions	
Define tree/plant health policies and response plans	64.2 %
Designate a tree/plant health lead on staff	63.0 %
Remove/destroy infested host plants and burn infected plant waste in situ	62.6 %
Regular removal of weeds and vegetal debris	61.8 %
Use of biopharmaceutical products (e.g., agrochemicals)	49.6 %
Monitoring actions	
Create public awareness and disseminate information	79.1 %
Define traceability/stock movement systems	50.8 %
Intensify phytosanitary practices along the entire supply chain	48.0 %
Monitor sentinel plants and sentinel plantings	44.9 %
Regular evaluation screening of soil substrates	37.0 %

3.3. Assessing the prioritised actions adopted by stakeholders

Educational approaches (i.e., public awareness and disseminating information, staff training on tree/plant health) and phytosanitary procedures (i.e., regular visual inspections and laboratory analyses) were the most commonly utilised actions for pest/pathogen management, while the least adopted actions concern the use of sanitation (i.e., washing stations for tools, boots, and vehicles) (Table 2).

The actions adopted according to the category of stakeholders are shown in Table 3. Different categories of stakeholders prioritised different actions according to their specific tasks. The results show that raising public awareness and disseminating information was commonly adopted by three categories of stakeholders (i.e., Advice Influence, Retailers and Site Vectors). The category of Retailers adopted a broader series of prevention (i.e., use regulated irrigation and drainage systems), management (i.e., define tree/plant health policies and response plans; designate a tree/plant health lead on staff) and monitoring (i.e., define traceability/stock movement systems) compared to the other categories of stakeholders. Two actions were mainly adopted by the category of Site Vectors, namely the use of biopharmaceutical products and the reliance on mains or treated water. Also, a set of actions were mainly adopted by Retailers and Consumers (i.e., training staff; exclusive use of certified plant material; removing of infested host plants and weeds and vegetal debris).

3.4. Mapping the networks between stakeholder

The results of the SNA showed a wide variability in the positive collaborations between stakeholders (Tables S4 and S5). Seven networks were developed corresponding to one for each category of stakeholders (Fig. 3). The results highlighted that Suppliers had positive relationships both within their own category and with the other categories of stakeholders, especially with Retailers and Consumers. Similarly, Site Vectors, Policy Regulation and Advice Influence were characterised by many positive relationships. In addition, it is important to point out that for Consumers, Policy Regulation and Advice Influence most of the collaborations were internal, within the same group of origin. Concerning Retailers and Consumers, they represented the categories with the greatest numbers of positive relationships and the highest average numbers of ties per stakeholder. Suppliers were the most influential and active category in three networks of other stakeholder categories (i.e. Retailers, Consumers, Transport Storage network).

4. Discussion

4.1. Stakeholders involved in urban tree biosecurity

The present study found a wide range of stakeholders with vested interests in urban tree biosecurity across European countries. With their varying core interests and prioritised agendas, these stakeholders can be positioned at different distances from the hands-on reality of urban tree

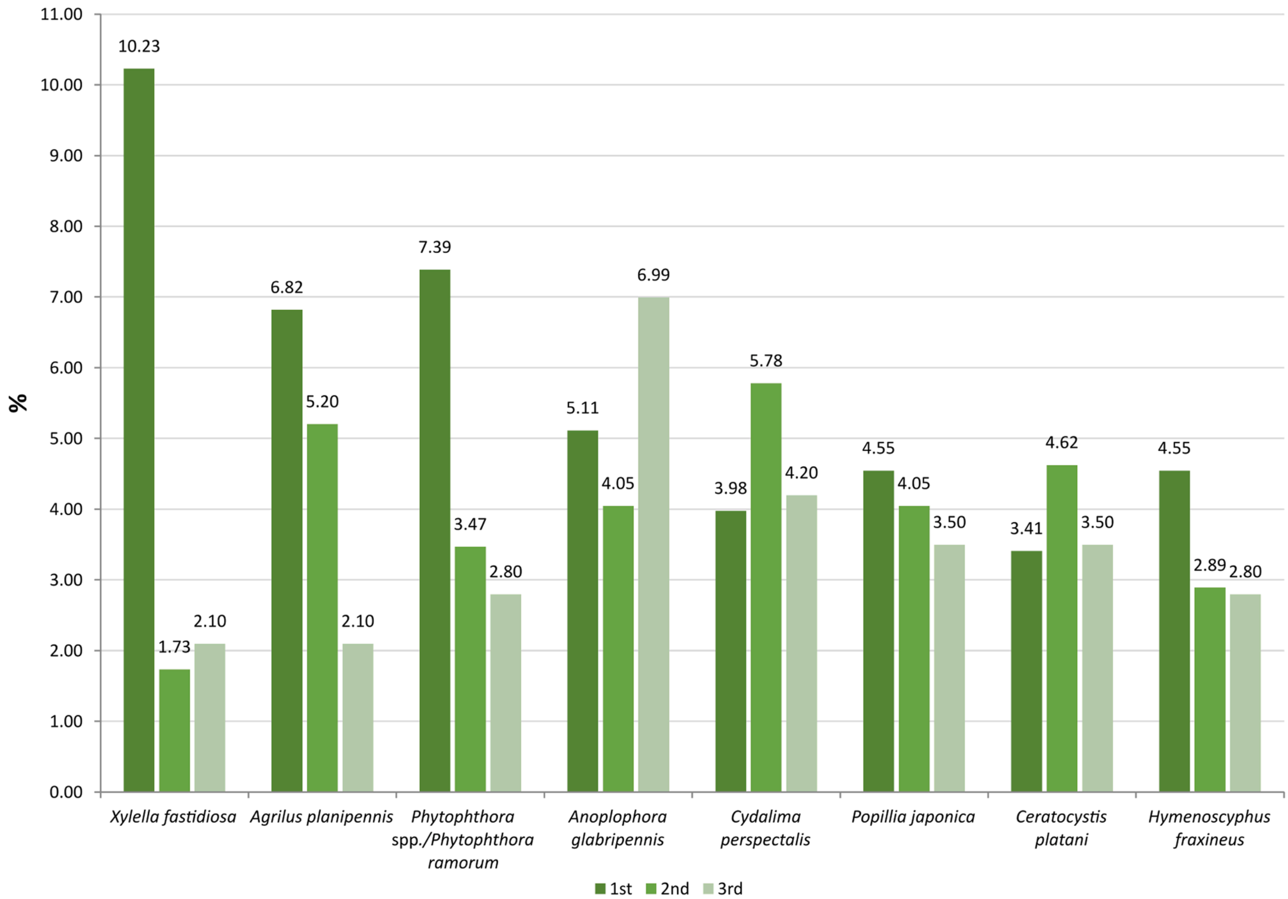

Fig. 2. The first, second, and third most significant future pests and pathogens in UGI, in accordance with the stakeholders' opinions (% on total answers).

biosecurity activities (Fig. 4), a position that reflects the type of decision-making characteristic for each group. Closest to the on the ground management activities are those involved in primarily operational decisions that focus on the day-to-day execution of tree care activities, requiring routine, predictability and consistency. These activities typically have a low level of interdependence, meaning they can be made independent but also easily delegated to others who are trained in arboriculture. At the other end of the spectrum are stakeholders engaged in strategic decisions that determine the long-term directions, visions, and goals, and involve setting priorities, allocating resources, and creating competitive advantages. Strategic decisions are often complex and highly interlinked with other decisions across the organisations. The different decision-making mode (e.g., analysis, judgment, and participative tactics) may explain some of the observed patterns in activity priorities and networking patterns (Harrington and Ottenbacher, 2009). In particular, high time pressure or urgency (e.g., the spread of a new invasive alien species affecting urban trees) may increase the use of the judgment tactic based on the intuition to guide the evaluation of alternatives. Conversely, the use of participatory tactics is suitable in highly complex situations where it is of key importance to include new ideas and specific knowledge provided by all stakeholder categories.

The stakeholder mapping resulting from this study showed that approximately a quarter of stakeholders belonged to the closest hands-on tree care group (Consumers and Site Vectors), another quarter slightly removed hands-on tree care group (Suppliers, Retailers and Transport Storage). The remaining half of stakeholders mapped belonged to the category of stakeholder furthest from the hands-on tree care group (Policy and Regulation and Advice Influence).

4.2. Knowledge about threats to urban green infrastructure

The findings of the study revealed a broad consensus among stakeholders on the main pests and pathogens of the European UGI, both current and in the future, confirming that stakeholders have a harmonised view of the major urban tree threats. This could be a result of standardised regulations, international collaboration, and shared knowledge across the stakeholder groups in different countries. However, the fact that a total of 184 current and future threatening urban tree pests and pathogens in Europe (Suppl. Table 1) were listed by the stakeholders' sample indicates a broad knowledge-pool that is well anchored in the local conditions. Some current threats to UGI reported in only a few countries are likely to become more important in a larger number of countries according to the respondents such as *X. fastidiosa* and *C. platani* which were listed as a current threat in five and four countries, and as a future threat in twelve and ten countries, respectively. Similarly, *A. planipennis* and *P. japonica* were listed as a current threat in three and four countries and are considered the main future threat in fourteen and six countries, respectively. Taken together, the stakeholders' knowledge and information from this study and recent scientific literature suggest that the attention of practitioners and policy makers should focus on preparation and prevention of new threats to UGI such as *A. planipennis*, *A. glabripennis*, and *P. japonica* in the future. *Agrilus planipennis* was first recorded in Europe in 2003 in Russia (Moscow city) and is currently spreading westward affecting the indigenous European ash in artificial plantings (Orlova-Bienkowskaja et al., 2020; Valenta et al., 2017). In fact, in 2019, *A. planipennis* was first detected in Ukraine (Markivka District, Luhansk Region) (Drogvalenko et al., 2019), and specifically in 2022 it was detected in the parks of Kyiv (Meshkova et al., 2024). *Anoplophora glabripennis* was recorded for the first time in Europe (Austria) in 2001, after which it spread to many

Table 3
Actions to prevent or manage pests and pathogens in UGI by category of stakeholders (blue: the actions adopted by more than 75 % of stakeholders within the same category; orange: the actions adopted by less than 25 % of stakeholders within the same category).

Action	Category of stakeholders						
	Suppliers (*n*=29)	Retailers (*n*=10)	Consumers (*n*=44)	Transport Storage (*n*=3)	Site Vectors (*n*=15)	Policy Regulation (*n*=35)	Advice Influence (*n*=119)
Prevention actions							
Staff training on tree/plant health (e.g. ID skills, legislation)	69%	80%	80%	67%	73%	77%	71%
Regular visual inspections and laboratory analyses	52%	70%	70%	67%	73%	60%	66%
Planting new trees or replacements made exclusively with certified plant material	72%	90%	75%	67%	67%	60%	55%
Reliance on mains or treated water	41%	60%	66%	0%	80%	37%	32%
Regulated irrigation and drainage systems which prevent puddling on-site	41%	80%	52%	0%	53%	29%	28%
Quarantining of new plants	34%	30%	20%	33%	47%	43%	34%
Washing station for plant pots and tools	55%	50%	41%	0%	40%	31%	25%
Boot washing station/disinfecting mat	38%	50%	30%	0%	7%	29%	22%
Vehicle washing station	21%	50%	34%	33%	13%	20%	14%
Management actions							
Define tree/plant health policies and response plans	52%	80%	68%	33%	67%	63%	61%
Designate a tree/plant health lead on staff	66%	100%	70%	67%	67%	57%	50%
Remove/destroy infested host plants and burn infected plant waste in situ	59%	90%	75%	0%	73%	51%	53%
Regular removal of weeds and vegetal debris	72%	100%	80%	67%	73%	51%	45%
Use of biopharmaceutical products	69%	70%	48%	33%	87%	43%	37%
Monitoring actions							
Create public awareness and disseminate information	62%	80%	70%	33%	80%	71%	82%
Define traceability/stock movement systems	66%	80%	50%	33%	47%	43%	42%
Intensify phytosanitary practices along the entire supply chain	62%	60%	43%	33%	47%	46%	42%
Monitor sentinel plants and sentinel plantings	59%	40%	39%	33%	40%	26%	45%
Regular evaluation screening of soil substrates	52%	70%	36%	0%	60%	34%	32%

European countries (France in 2003, Germany in 2004, Italy in 2007, the Netherlands in 2010, Switzerland in 2011, Finland and Montenegro 2015, and the UK in 2021) (Marchioro and Faccoli, 2021; Tomiczek et al., 2002). *Popillia japonica* was first recorded in 2014 in northern Italy, and in 2019 it was classified as the second most crucial potential priority pest in Europe (Gotta et al., 2023; Sánchez et al., 2019). In addition, practitioners and policy makers should pay particular attention to *C. platani* which, since it first appeared in Italy in 1972 and in France in 1974, has continued to increase its spread in Europe (e.g., Switzerland, Spain, Greece, Turkey, Albania), as highlighted by Tsopelas et al. (2017). The impact of *C. platani* in the Mediterranean region of Europe is very serious in the urban context, considering the diffusion of the plane tree species in street trees and parks. Similarly, *X. fastidiosa* also deserves special attention for its increasing diffusion in many Mediterranean European countries (e.g. France, Italy, Portugal, Spain) and its ability to attack new host plants in addition to the olive tree (*Olea europaea*), such as *Spartium junceum*, *Nerium oleander*, *Lavandula* sp., and *Rosmarinus* sp. (Trkulja et al., 2022).

4.3. Prioritised biosecurity actions

The outcome of this study revealed a varied palette of actions adopted to counter IAPPs. Most respondents identified awareness raising and dissemination of information to staff and the public as the strategy of choice. However, earlier studies have shown that knowledge and awareness about biosecurity is rather low amongst the general public (Dunn et al., 2020; Fuller et al., 2016; Urquhart et al., 2017b). For this reason, developing forms of involvement with users and visitors in urban green spaces – such as citizen science initiatives, the use of voluntary networks to disseminate information and the inclusion of local communities in multidisciplinary teams (Crow et al., 2020; Hulbert et al., 2023) – could be a useful strategy. Being more informed about urban tree threats could encourage biosecure behaviours. For forest and horticultural professionals, training and updating of staff in charge of managing the health of trees was the second most popular action. In earlier studies, this action has been found to be important in management of existing pests and pathogens whilst preparing for the future (Marzano et al., 2021; Sutcliffe et al., 2018). The third most widely adopted action was the regular visual inspections and laboratory analyses, that needs of trained and experienced staff (Marzano et al., 2021). Willingness to use some actions, such as reliance on treated water sources and improvement of drainage system to avoid puddles and on-site quarantining, may have been reduced because they were considered expensive or challenging from an organisational and spatial point of view (Marzano et al., 2021; Marzano et al., 2016). In general, the actions of cleaning/disinfecting vehicles, boots and tools were the least adopted actions. In fact, these actions are expensive to implement and difficult to maintain as highlighted by Marzano et al. (2016). Interestingly, straightforward on-site measures, such as the use of boot and vehicle washing stations, were deemed much lower in priority compared to long-term, indirect actions such as training. This is notable despite the potential of on-site hygiene to curb the spread of certain

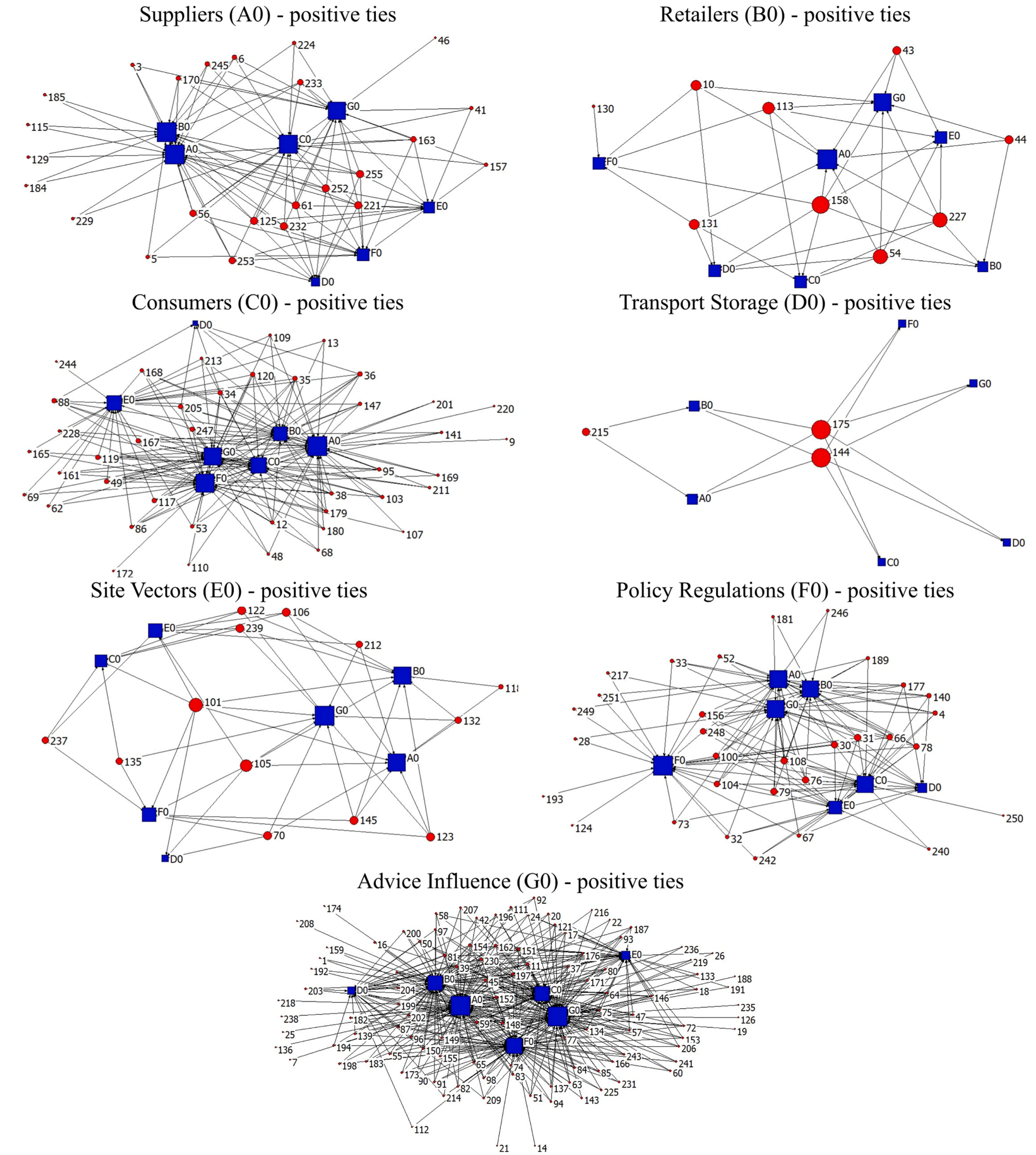

Fig. 3. Networks of positive collaborations between stakeholders by category. Red circles are the individual stakeholders (with respective numeric ID) involved in the survey that belong to the reference category. Blue circles are the other stakeholder categories indicated by the individual stakeholders. The size of the shapes refers to the centrality values (larger circles correspond to higher centrality values), while the lines are the ties.

pathogens, such as soil-borne *Phytophthora* species (Liew et al., 2023; Brasier et al., 2022).

Considering the results by stakeholder category, it is important to highlight that the Transport Storage did not implement many actions, but it should be noted that the sample of this category was represented only by three respondents and many of the actions in the list are not usual activities performed by this category. The quarantining of new plants was the prevention action least adopted by Consumers.

Finally, except for the Transport and Storage category, stakeholders in all categories implemented all actions to at least a certain degree, and especially Retailers had adopted several of the actions to high degree. This suggests that actors in Retailers category (e.g., nurseries, garden

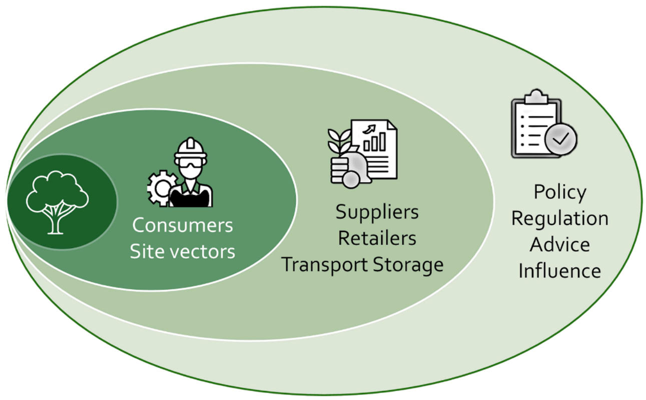

Fig. 4. Stakeholder categories distribution based on the proximity to the hands-on practice of tree care.

centres) were likely to be well informed about the biosecurity risks and had invested in prevention, management and monitoring actions. Interestingly, quarantining of new plants was of low priority also in the category of Retailers, although it could be a highly efficient biosecurity method. Joint efforts to promote and facilitate use of quarantining would thus be needed, including development of specific standards and guidelines for UGI, as well as financial incitements and subsidies.

4.4. Stakeholder networks

A wide variety of relationships between the different categories of stakeholders was detected, confirming the previous result that biosecurity necessarily involves networks of relationships between stakeholders involved in the management and control of IAPPs (Reed and Curzon, 2015). In addition, a network of effectively interconnected stakeholders can enable productive progress in decision making and the pursuit of common goals through effective strategies (Ambrose-Oji et al., 2024). Therefore, an important aspect of this study was to analyse the networks of influence and knowledge flows among stakeholders, aiming to identify strong positive relationships to consolidate and the weaker ones to strengthen.

Our analysis showed that positive collaborations tended to follow a gradient based on the proximity of the stakeholders to the hands-on practice of tree care (Fig. 4). In fact, the results showed intense positive collaborations between Supplier, Retailers and Transport Storage on one side and partially between Consumers and Site Vectors on the other side. This could be an indication that there are intense collaborations among stakeholders that have the same proximity to the hands-on practice of tree care. The two categories furthest from the hands-on practice of tree care (i.e., Advice Influence and Policy and Regulation) were those with the most conflicting relationships with the other categories and also between them. This may be an obstacle for the development of more efficient biosecurity, considering that stakeholders involved in biosecurity need solid scientific foundations on which to take effective decisions in terms of prevention and mitigation (Sutcliffe et al., 2018). Therefore, activities bridging the science-society gap – such as through science communication and outreach using multiple platforms and in close collaboration with media, investing in science education at different levels – should be a high priority for the researcher community. The relationship between policy makers and civil society (i.e., Policy and Regulation and Consumers) is another weak network that needs to be strengthened, as policy makers tend to be particularly influenced in their decisions by public opinion to ensure social acceptability (Urquhart et al., 2017a). A key role could be played by civil society organizations and citizen groups, in order to strengthen the collaboration between policy makers and citizens. These organizations, by collecting and organizing the demands of individuals, have the potential to strengthen the institutional accountability and make governments more responsive to society's demands (Court et al., 2006). In other words, these organizations and groups should be a privileged collector of individual requests. A positive collaboration and mutual trust between policy makers and civil society organizations can make more transparent and inclusive the drafting of regulatory policies related to urban pest and pathogen management (Raum et al., 2023). In addition, the non-expert public, despite a low level of knowledge on tree biosecurity, demonstrate a high level of concern about outbreaks (Fuller et al., 2016), especially in the presence of scientific uncertainty (Urquhart et al., 2017b). Citizen science projects that focus on pests and pathogens most commonly identified by stakeholders are a potential avenue for channelling these concerns in support of biosecurity efforts (Gupta et al., 2022). Several studies also highlight the need to strengthen the direct involvement of policy makers in citizen science initiatives (Norman-Burgdolf and Rieske, 2021; Pocock et al., 2019; Schade et al., 2021), in order to improve the coherence of policies and programs with community needs and to address regulatory gaps and mismatches (Guerrini et al., 2018; Marks et al., 2023).

5. Conclusions

The results of this study provide insights from one of the first international studies on the priorities and networks of stakeholder groups involved in urban tree biosecurity. It highlights the extensive knowledge about individual threats possessed by the stakeholders and calls for innovative ways to utilise this knowledge for the design of proactive biosecurity measures and actions. This study should be considered a preliminary basis for further involvement of more European countries and more stakeholders from each country. Indeed, the main weakness of this study is the non-representative sample of stakeholders from some countries whose response rate was less than 25 %. In addition, the stakeholder analysis, although conducted in all countries using the same methodology, identified a very variable number of stakeholders from country to country. Finally, it can be argued that a more detailed knowledge of the network of collaborations between different categories of stakeholders can help to concentrate efforts to improve the current biosecurity system. The collaboration and active involvement of all categories of stakeholders is clearly needed for effective management and control actions against pests and pathogens that threaten urban trees.

CRediT authorship contribution statement

Johanna Witzell: Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Zuzana Dobšinská:** Investigation, Data curation. **Brynja Hrafnkelsdóttir:** Investigation, Data curation. **Anna Maria Vettraino:** Investigation, Data curation. **Julio Javier Diez Casero:** Investigation, Data curation. **Milica Zlatković:** Investigation, Data curation. **Ilija D. Đorđević:** Investigation, Data curation. **Martina Kičić:** Investigation, Data curation. **Liina Jürisoo:** Investigation, Data curation. **Magdalena Kacprzyk:** Investigation, Data curation. **Yasin Korkmaz:** Investigation, Data curation. **Kahraman İpekdal:** Investigation, Data curation. **Zuzana Jánošíková:** Investigation, Data curation. **Tarik Trestić:** Investigation, Data curation. **Katalin Tuba:** Investigation, Data curation. **Jitka Meňházová:** Investigation, Conceptualization. **Alessandro Paletto:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Saša Orlović:** Investigation, Data curation. **Carlotta Sergiacomi:** Writing – original draft, Methodology, Data curation, Conceptualization. **Diana Marčiulynienė:** Investigation, Data curation. **Dinka Matošević:** Investigation, Data curation. **Špela Pezdevšek Malovrh:** Investigation, Data curation. **Marta Bełka:** Investigation, Data curation. **Leopold Poljaković-Pajnik:** Investigation, Data curation. **Kathrin Blumenstein:** Investigation, Data curation. **Carmen Morales-Rodríguez:** Investigation, Data curation. **Mariella**

Marzano: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Irena Papazova-Anakieva:** Investigation, Data curation. **Mersudin Avdibegović:** Investigation, Data curation. **Daiva Burokienė:** Investigation, Data curation. **Ana Paula Ramos:** Investigation, Data curation. **Helena Bragança:** Investigation, Data curation. **Manuela R. Branco:** Investigation, Data curation. **Zane Lībiete:** Investigation, Data curation.

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

The authors would like to thank all the participants who kindly dedicated their time during the stakeholders' analysis process. This article is based upon work from COST Action *Urban Tree Guard - Safeguarding European urban trees and forests through improved biosecurity (UB3Guard)*, CA20132, supported by COST (European Cooperation in Science and Technology). The study was also developed with the support of the Short-Term Scientific Mission "Stakeholder analysis and survey on the topic of urban tree infrastructure biosecurity" carried out within the CA20132 during June 2022 at the Department of Forest and Wood Products Economics and Policy of the Faculty of Forestry and Wood Technology at the Mendel University in Brno (Czech Republic). Milica Zlatković, Saša Orlović and Leopold Poljaković-Pajnik acknowledge funding support from the Ministry of Science, Technological Development and Innovation of the Republic of Serbia. Milica Zlatković and Saša Orlović also acknowledge the Centre of Excellence Agro-U-For. Magdalena Kacprzyk was financially supported by the Ministry of Science and Higher Education of the Republic of Poland for the University of Agriculture in Krakow (SUB/040013-D019). Manuela Branco was supported by FCT – Fundação para a Ciência e a Tecnologia, I.P., Projects UIDB/00239/2020 (DOI 10.54499/UIDB/00239/2020) and UIDP/00239/2020 (DOI 10.54499/UIDP/00239/2020). Ana Paula Ramos was financially supported by the FCT-Fundação para a Ciência e a Tecnologia (Portugal) unit LEAF (UIDB/04129/2020 and UIDP/04129/2020). The authors would like to thank Glyn Jones, Jon Stokes, and Eeva-Maria Tuhkanen.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2025.128674.

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