Journal of Pest Science (2023) 96:903–919
https://doi.org/10.1007/s10340-023-01591-y

REVIEW

# Zoning strategies for managing outbreaks of alien plant pests in the European Union: a review

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Received: 7 June 2022 / Revised: 9 December 2022 / Accepted: 6 January 2023 / Published online: 19 January 2023


## Abstract
Managing outbreaks of alien plant pests is key to preserving biodiversity and safeguarding crop production. Zoning strategies are applied by plant health authorities to tailor measures to the risk of spread in relation to distance from the outbreak epicentre and the biology of the pest. Here we synthesize information on outbreak management to evaluate the diversity and consistency of such approaches. We collected information on the zoning strategies of 121 outbreaks of 25 plant pests in the European Union (EU). According to the organism's presence and the measures applied, five zones were distinguished: an infested zone (83% of cases), a buffer zone (76%), a clear-cutting zone (28%), an eradication zone (1%) and a containment zone (1%). Infested zones and buffer zones were adjacent non-overlapping zones, while the clear-cutting zone, eradication zone or containment zone was within either the infested zone or buffer zone. A combination of infested and buffer zones was used in 51% of recorded cases. Measures differed within different zones. Destruction of infested plants in the infested zone was done in 78% of the cases, while surveillance was always applied in the buffer zone. Regulation of an organism at EU level led to a convergence of zoning strategies applied by different member states. Regulations often prescribed the greatest widths used before regulations were issued. Further analyses are needed to explore the efficacy of different strategies including the costs of each strategy. Such analyses should combine insight from practice with bio-economic modelling.

**Keywords** Combination of zones · Containment · Eradication · Phytosanitary measures · Plant pests · Widths of zones · Zone diversity

## Introduction

Alien plant pests threaten plants that are important for ecosystem services and biodiversity and for agriculture. To prevent the entry of new plant pests, governments regulate trade with potential to introduce plant pests, e.g. by restricting imports of certain goods or by imposing phytosanitary requirements for traded plants, such as fumigation. However, these preventive measures do not completely prevent the arrival of new plant pests (Liebhold et al. 2012; Epanchin-Niell 2017), and thus, effort is also directed towards managing outbreaks of introduced or established plant pests with expected high impact (Barron et al. 2020). Here, we follow the definition of outbreak as used by the International Plant Protection Convention (IPPC) which is "a recently detected pest population, including an incursion, or a sudden significant increase in an established pest population in an area" (FAO 2021). Within this paper, we focus on outbreaks of

Communicated by Jay Rosenheim.

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non-native pests, i.e. those pests that have been newly introduced into an area.

Outbreak management needs to consider many aspects: what is effective given the biological properties of the plant pest and uncertainty in knowledge about these properties, what is required by the legal framework, what are the available resources to manage the outbreak and what is the social and geographical context in which the outbreak occurs (Ward 2016). In the European Union (EU), if a pest is not regulated at the EU level, a member state may manage a pest outbreak according to what is considered most appropriate. A non-regulated pest, i.e. a pest that is not explicitly mentioned in the EU plant health law (European Union 2019), does not need to be reported to supranational organizations. If a pest has an unacceptable economic impact and poses a threat to the EU, it may be regulated by the EU, resulting in a species specific legislation that specifies the required measures for surveillance and outbreak management, including the delimitation of zones, their widths and required control measures if an outbreak is detected (European Commission 2002, 2007, 2008a, b, 2018, 2019; European Union 2003, 2012a, 2015, 2016). For details regarding the legal framework for decision-making of zoning strategies in the EU, we refer to Appendix S1.

When outbreaks occur, the area around the findings may be divided into different zones to create clarity on which measures are applied where. Zones are delimited according to the presence of the pest in the area and are meant to isolate or separate populations of infested plants from populations of non-infested plants. The spread of a pest from an infested to a non-infested zone can be restrained by destroying infested or potentially infested host plants in the infested zone, and also by prohibiting movement of plant material out of the infested zone. Furthermore, zoning allows measures to be limited to a specific zone, minimizing the impact of the measures. There is surprisingly little overview on zoning strategies in the domain of plant pests, except for some modelling literature which aims to evaluate the effectiveness of zones in case studies (Carrasco et al. 2010; White et al. 2017; Rimbaud et al. 2019; Robinet et al. 2020; Cendoya et al. 2022). There are also few published general guidance documents on zoning strategies for practitioners. Only recently, a guideline on the design and implementation of buffer zones was published (EPPO 2021a).

As a result, it is not well established for plant pests which type of zones are commonly used, what their widths are and which measures are commonly taken in each zone. It is therefore useful to make a synthesis of how zoning for management of outbreaks of plant pests is currently done in practice. In Europe, much information on the actual management of outbreaks of plant pests is described on a case by case basis in reports of plant protection organizations, such as the European and Mediterranean Plant Protection Organization (EPPO) and National Plant Protection Organizations (NPPOs), and published literature (Macleod et al. 2004; Cannon et al. 2007; Vukadin 2010; Hérard and Maspero 2019; Eyre and Barbrook 2021). However, these reported zones are not always defined in a consistent way due to the occurrence of synonyms (different terms with the same meaning) and homonyms (a single term with multiple meanings). In outbreak reports, zones may be described implicitly by stating that zones were demarcated in accordance with the relevant EU legislation.

The aim of this paper is to provide a synthesis of how zoning is done in practice in the EU, and to identify potential targets for research to support evidence-based outbreak management. We focus in particular on the following questions: (1) What is the general outbreak management process for regulated plant pests? (2) Which zones are delimited and which combination of zones are used, and which terms are used, and which synonyms or homonyms are used for which zone? (3) What are the zone widths that are used and which measures are taken in various zones? (4) How do regulation and infestation size affect the zoning strategy? We answer these questions by reviewing the outbreak management reports provided by the EPPO Global Dataset, and by checking relevant EU regulations.

## Methodology

First, we established a list of plant pests that could be used for our study. For early warning of emerging pests, EPPO maintains an A1 and an A2 list consisting of plant pests which potentially present a risk to EPPO member countries and are recommended for regulation as quarantine pests (EPPO 2017). The A1 list contains pests which are absent from the EPPO region while the A2 list includes pests that are present but not widely distributed in the EPPO region (EPPO 2020). Besides, EPPO maintains an EPPO Alert List to draw the attention of member states to pest species that are not (yet) recommended as quarantine pests but can be subjected to a Pest Risk Analysis (EPPO 2022). The EU maintains a list of quarantine pests and regulated non-quarantine pests, and associated measures on plants and plant products to reduce the risk of alien pest introduction to an acceptable level (European Union 2019). The EPPO A1 and A2 lists, the EPPO Alert List and the EU list are not identical although there is overlap. To search for outbreak cases of plant pests, we compiled a list of candidate plant pests that had caused outbreaks in the EU by combining the EPPO A1 and A2 lists, the EPPO Alert List and the EU list of regulated pests (European Union 2019; EPPO 2020). We searched the EPPO Global Database (https://gd.eppo.int/) for outbreak reports of the pests on this list. We concentrated on outbreaks that occurred between 1975 and 2020. Taxonomically, plant pests can be bacteria and phytoplasmas, fungi, insects, mites, molluscs, nematodes, parasitic and invasive plants, viruses and virus-like organisms that are damaging to plants or plant products. In our research, we focused on management of outbreaks of insects, pathogens (bacteria and phytoplasmas, fungi, viruses and virus-like organisms) and nematodes. We excluded mites, parasitic and invasive plants, and molluscs (*Pomacea*) because no outbreaks with information on zoning were available in the EPPO Global Database.

Second, to analyse outbreak reports in a consistent way, we formulated definitions of the infested zone, the buffer zone and the clear-cutting zone (Table 1). Using these definitions we identified the use of synonyms and homonyms in the naming of zones in the outbreak reports in the EPPO Global Database. We based our definition of an **infested zone** on the EU regulation for *Anoplophora glabripennis*: "an infested zone is the zone where the presence of the specified organism has been confirmed, and which includes all plants showing symptoms caused by the specified organism and, where appropriate, all plants belonging to the same lot at the time of planting" (European Union 2015). A **buffer zone** was defined based on the EU regulation, International Standards for Phytosanitary Measures (ISPM) 5 and measures in the buffer zone from EPPO reports as: an area with a specific radius beyond the boundary of the infested zone (European Union 2015), aimed to minimize the possibility of spread of the target pest out of the infested zone (ISPM 5, FAO 2021), and which may contain no known infested plants and, where at least surveillance is conducted and/or other phytosanitary measures, e.g. conducting public awareness campaigns, can be included to verify the absence of pest in this area (EPPO 2021b). Based on the EU regulations, we defined a **clear-cutting zone** as: an area with a specific radius around individual infested plants or around the infested zone where complete clearance of hosts is conducted (European Union 2012b, 2015).

Three steps were used to infer the zones that were used from reports (Fig. 1). From each outbreak report with information on zoning, we extracted information on species, status in the EU, location, country, date, infestation size, goal, EU regulation, inferred zones and on which step this inference was based (Fig. 1), alternative names for defined zones, measures in defined zones and their widths for the plant pests in our identified list (Table 2, Appendix S2). We derived a scheme of the general outbreak management process for regulated pests by reviewing the outbreak cases. We expected that the implemented zoning strategies would vary between member states before regulation of a pest but would converge after regulation. We used Pearson´s chi squared tests ($\alpha = 0.05$) to determine if the proportion of cases that were delimited with the combination of zones prescribed in regulation differed before and after the regulation, and to determine if the proportion of cases that were managed with at least two zones varied with infestation size. Cases used for the analysis are listed in Appendix S2.

## Results

### Species selection

Merging the EPPO A1 and A2 lists, EPPO Alert List and EU list of regulated plant pests resulted in a list of 295 insect species, 667 pathogen species and 39 nematode species. Of those species, 71 insect species, 49 pathogen species and 11 nematode species had outbreak reports in the EPPO Global Database. Of these, information on the actions taken was available for 55 insect species (337 outbreak reports), 39 pathogen species (300 outbreak reports) and 9 nematode

**Table 1** Definition of zones in this paper

| Terminology | Definition |
|---|---|
| Infested zone | The zone where the presence of the specified organism has been confirmed, and which includes all plants showing symptoms caused by the specified organism and, where appropriate, all plants belonging to the same lot at the time of planting (European Union 2015) |
| Buffer zone | An area with a specific radius beyond the boundary of the infested zone (European Union 2015), aimed to minimize the possibility of spread of the target pest out of the infested zone (ISPM 5, FAO 2021), and which may contain no known infested plants and, where at least surveillance is conducted and/or other phytosanitary measures, e.g. conducting public awareness campaigns, can be included to verify the absence of pest in this area (EPPO 2021b) |
| Clear-cutting zone | An area with a specific radius around individual infested plants or around the infested zone where complete clearance of hosts is conducted (European Union 2012b, 2015) |

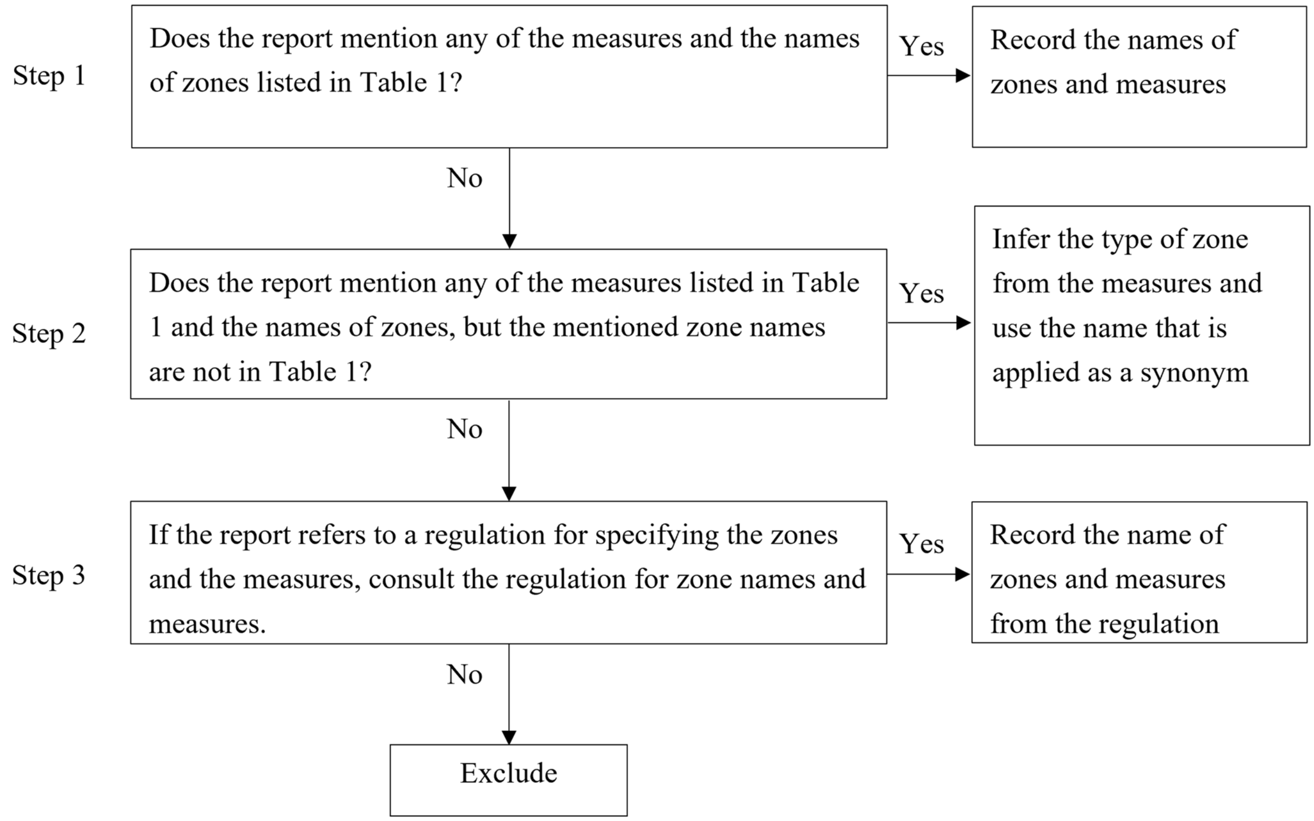



**Fig. 1** Steps for inferring zoning strategies based on outbreak reports extracted from the EPPO Global Database (https://gd.eppo.int/) to interpret reported zones in a consistent way. Inconsistencies in reported zones may arise due to the use of synonyms, homonyms or implicit definitions on zones

**Table 2** Variables extracted for each outbreak from the description in EPPO reports

| Variable | Definition | Data type/Unit |
|---|---|---|
| Species | The scientific name of the plant pest that caused the outbreak in the EU | Text |
| Status in the EU | The regulatory status of the plant pest in the EU | Text |
| Location | The specific location of the detection | Text |
| Country | The country in which the outbreak was detected | Text |
| Date | The time at which the outbreak was detected | Date |
| Infestation size | The infestation size of the outbreak when it was detected | Continuous ($m^2$) |
| Goal | What should the outbreak management programme achieve | Text |
| EU regulation | The EU regulation in which harmonized measures were regulated to manage the outbreak of a plant pest | Text |
| Defined zones and based steps | Zones that were delimited to manage the outbreak of plant pests and the steps in Fig. 1 that were used to infer defined zones | Text |
| Alternative names for defined zones | Alternative names for defined zones | Text |
| Measures in defined zones | Measures in defined zones | Text |
| Width of defined zones | The radial width of defined zones | Continuous (m) |

species (42 outbreak reports). Information on the zoning strategy used was reported for 10 insect species (64 outbreak reports), 13 pathogen species (50 cases) and 2 nematode species (7 outbreak reports) (see Fig. 2 for a flowchart, Appendix S2). The proportion of pathogens and insects were comparable in the final set of selected cases and the set of

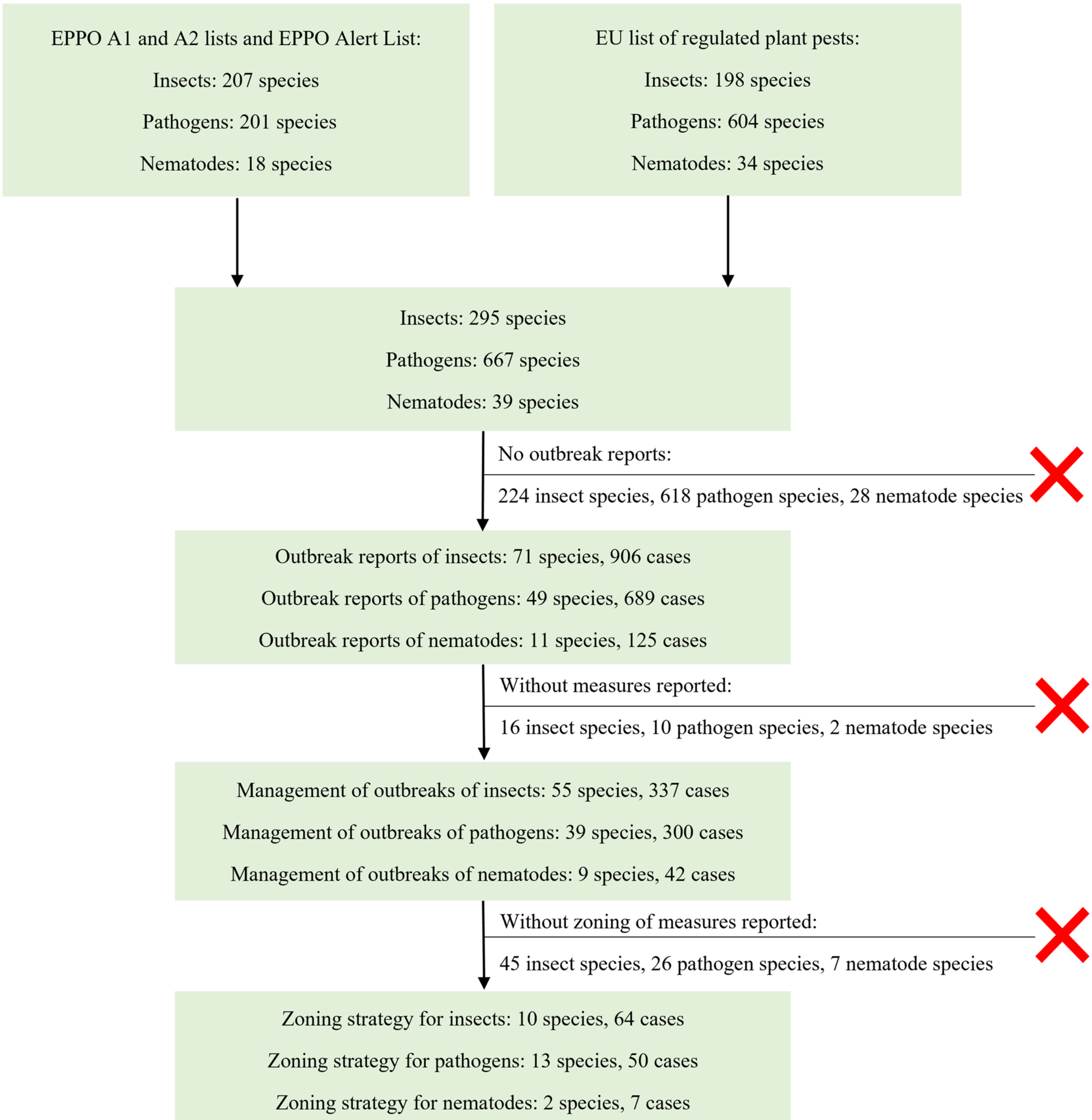



**Fig. 2** Species selection. A plant pest list for data collection was compiled by merging the EPPO A1 and A2 lists, EPPO Alert List and the EU list of regulated plant pests. Zoning strategies for the outbreak cases of insects, pathogens and nematodes were extracted after excluding the cases without reports

excluded cases (41% vs 45% pathogens). The set of selected cases contained more regulated species (96%) than the 558 excluded cases (57%). However, the pest species in the two sets (included and excluded) were similar in terms of economic importance, introduction and spread risk.

## The general outbreak management process for regulated pests in practice

We were able to describe zoning strategies for 121 outbreak cases on the basis of information in the EPPO Global Database (see Supplementary material Appendix

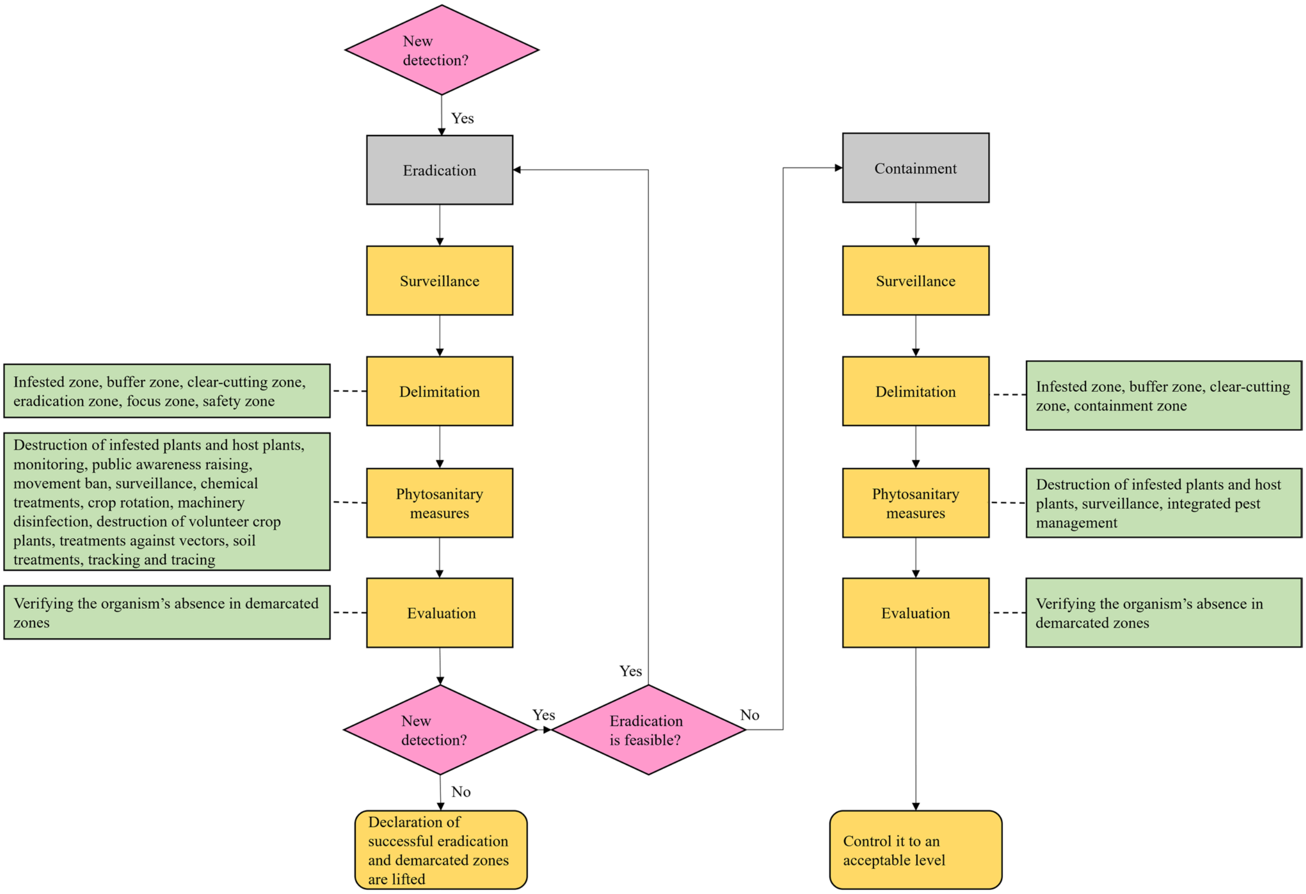



**Fig. 3** Flow chart showing the implementation process of zoning strategies for managing outbreaks of regulated plant pests in the EU. *Grey rectangles* indicate the management goal, *yellow rectangles* indicate the components of implementation steps, *green rectangles* give further detail and actions taken, *pink diamonds* indicate decision-making, *arrows* indicate a causal or time sequential relationship, starting from the step of cause and pointing to the step of effect, and *dashed line*s indicate a parallel relationship, connecting general implementation steps (*yellow rectangles*) and the associated actions (*green rectangles*). The scheme is derived on the basis of reviewing outbreak reports of 24 regulated species with zoning strategies applied

S2). Of the 121 outbreaks, 118 outbreaks were caused by 24 EU regulated pests. Based on the 118 outbreak cases, we deduced the general outbreak management process for regulated pests (see Fig. 3 for a summary flowchart):

1) The initial goal of outbreak management for regulated pests is always eradication. The aim may shift to containment if eradication appears not feasible.
2) Once the goal of eradication is determined, the area surrounding an outbreak area is divided into zones, each with a different set of measures. Demarcated zones most often comprise an infested zone and a buffer zone. We found that an infested zone (implemented in 100 out 121 cases), buffer zone (92 out of 121 cases), clear-cutting zone (34 out of 121 cases), eradication zone (1 out of 121 cases) and containment zone (1 out of 121 cases) were delimited, in different combinations. Measures within each zone are elaborated in "The diversity of zoning strategies in practice" section.
3) Once a new finding is made in the buffer zone, the infested zone is expanded such that it includes the newly infested site. The buffer zone is also adjusted. If a new outbreak is detected outside the buffer zone, a new infested zone and buffer zone will be delimited around the new finding. Depending on the geographic location of the new infested site compared to the previous one and the width of the zones, the two infested zones could share one buffer zone around the two infested zones. This means that the contiguity of the old and new demarcated zones is related to the spatial position of the new outbreaks and the width of the existing zones.
4) Successful eradication is declared and demarcated zones are lifted if no detection occurs over a specified period, in accordance with the biology of the organism. The specified period is defined as at least one life cycle and

some additional years. For example, to guarantee eradication of *Anoplophora chinensis*, demarcated zones can only be lifted if the pest is not detected for at least four consecutive years, which period includes one life cycle of 3 years plus one additional year (European Union 2012b). If a new detection is made in the demarcated zones and the evaluation shows that eradication is feasible, eradication measures would be implemented again.

5) If a pest becomes widely distributed and experience in other countries indicates that eradication may not be feasible, NPPOs can switch from eradication to containment and this switch is specified in the EU legislation. For example, NPPOs were obliged to implement measures to eradicate *Xylella fastidiosa* in accordance with the EU regulation after it was first detected in Lecce province, Italy (Box 1). However, after several years it became clear that eradication in Lecce was not feasible and measures were adapted to aim for containment of *X. fastidiosa* in Lecce (European Union 2016).

## The diversity of zoning strategies in practice

### Zones delimited and synonyms and homonyms in naming zones

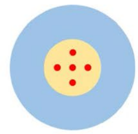
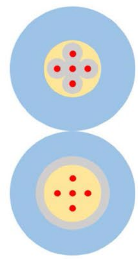
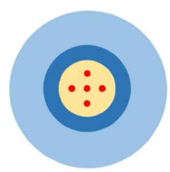
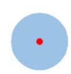
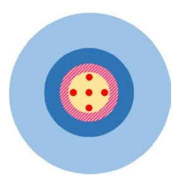
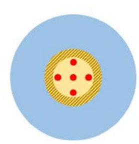
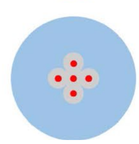
There was substantial variation in the zoning strategies applied in these 121 outbreaks. Synonyms and homonyms were used to describe different zones (Table 3). For example, the infested zone was also referred to as affected area, focus zone, safety zone, infected area/site/zone, outbreak area/site, infested area/site or quarantine area/zone. The buffer zone was also referred to as safety zone, focus zone and surveillance zone. The safety zone and focus zone that were delimited around the infested zone were special buffer zones for managing the insect pests *Diabrotica virgifera virgifera* and *Dryocosmus kuriphilus*, respectively, where surveillance was implemented to verify that the pest did not spread outside the infested zone. The term "surveillance zone" was used to describe the outer part of the buffer zone, which was used to detect further spread of the pest beyond the primary buffer zone where host plants were treated with insecticide when managing *Trioza erytreae* in Portugal, in 2020, and *X. fastidiosa* in Italy, 2015 (Appendix S2, ID 46, 82). The clear-cutting zone was also referred to as clearcut area when managing *A. glabripennis* in the Netherlands, 2012 (Appendix S2, ID 31), or focus zone when managing *Bursaphelenchus xylophilus* in Spain, 2008 (Appendix S2, ID 114). We found two homonyms, i.e. terms with multiple meanings: safety zone (either infested zone or buffer zone) and focus zone (either infested zone, clear-cutting zone or buffer zone).

Different zones described above were used in different combinations (Table 4). In total, ten different combinations were found, of which the combination "infested zone + buffer zone" was used most often (62 out of 121 cases). For the combination "infested zone + clear-cutting zone + buffer zone" (15 out of 121 cases), the clear-cutting zone was delimited either around individual infested plants (12 out of 15 cases) or around the infested zone (3 out of 15 cases). In some cases, a strict eradication measure of clear-cutting was implemented in the outer part of the infested zone to reduce the likelihood of the organism spreading into the buffer zone. In managing *X. fastidiosa*, this outer part

**Table 3** Terms used for outbreak management. The first column is the term of zones following the definition in Table 1. The second column refers to synonyms that were used; the third column contains the unique ID for each outbreak case to link to the outbreak reports in Appendix S2. The homonyms of "safety zone" and "focus zone" are marked in italic

| Type of zones | Synonyms | Case ID in Appendix S2 |
|---|---|---|
| Infested zone | Affected area | 7 |
| | *Focus zone* | 8, 44, 45, 49, 50, 55, 57, 58, 59, 60, 61, 62, 63, 64, 66, 86 |
| | Infected area | 70, 71, 72, 73, 74, 81 |
| | Infected site | 89, 111, 119, 120, 121 |
| | Infected zone | 94, 95 |
| | Infested area | 9, 10, 11, 14, 18, 20, 26, 28, 43, 47 |
| | Infested site | 5, 13, 19, 32, 100 |
| | Outbreak area | 28, 52 |
| | Outbreak site | 33, 96 |
| | Quarantine area | 17, 39, 48, 51, 54, 56 |
| | Quarantine zone | 21, 67, 68, 69 |
| | *Safety zone* | 65, 118 |
| Buffer zone | *Safety zone* | 45, 49, 50, 52, 53, 55, 57, 58, 59, 60, 61, 62, 63, 64 |
| | Surveillance zone | 46, 82 |
| | *Focus zone* | 38, 40 |
| Clear-cutting zone | Clearcut area | 31 |
| | *Focus zone* | 114 |

**Table 4** Graphical illustration of ten different combinations of five zones (infested zone, buffer zone, clear-cutting zone, eradication zone and containment zone) that have been used to manage outbreaks in the EU. Information was available for managing the outbreaks of 121 cases. *Red points* represent infested plants, *yellow circles* represent the infested zone, *blue circles* represent the buffer zone, *grey circles* represent the clear-cutting zone, *pink hatched lines* represent the eradication zone, and *yellow hatched lines* represent the containment zone. Infested zones and buffer zones were not overlapping. Clear-cutting zones were overlapping with either the infested zone or the buffer zone. Containment zones and eradication zones were overlapping within the outer part of the infested zone

| Combination of zones | Illustration | Number of cases |
|---|---|---|
| Infested zone (yellow) around infested plants (red dots) + buffer zone (blue) |  | 62 |
| Clear-cutting zone (grey) |  | 17 |
| Infested zone + clear-cutting zone[1] + buffer zone |  | 15 |
| Infested zone |  | 11 |
| Infested zone + primary buffer zone (dark blue) + secondary buffer zone (light blue)[2] |  | 9 |
| Buffer zone around a single infested plant |  | 3 |
| Infested zone + eradication zone[3] (pink hatched) + primary buffer zone + secondary buffer zone[2] |  | 1 |
| Infested zone + containment zone[4] (yellow hatched) + buffer zone |  | 1 |
| Infested zone + clear-cutting zone |  | 1 |
| Clear-cutting zone + buffer zone |  | 1 |

[1]Clear-cutting zone can be delimited either around individual infested plants (12 out of 15 cases), or around an infested zone as a whole (3 out of 15 cases). The clear-cutting zone was delimited around an infested zone when managing *Anoplophora chinensis* in the Netherlands, 2009, *Bursaphelenchus xylophilus* in Portugal, 2008, and *B. xylophilus* in Spain, 2018 (Appendix S2, ID 12, 113, 117).

**Table 4** (continued)

[2]The secondary buffer zone, i.e. the outer part of the buffer zone, is called the surveillance zone when managing *Trioza erytreae* in Portugal, 2020 and *Xylella fastidiosa* in Italy, 2015 (Appendix S2, ID 46, 82).

[3, 4]The position of the eradication zone and containment zone was within the infested zone and adjacent to the buffer zone when managing *X. fastidiosa* in Italy in 2015 and 2016, respectively (Appendix S2, ID 82, 83). The applied measures were different in these two zones (Box 1).

**Table 5** Width of the clear-cutting zone in metres. Distinction is made between pest status, width in practical outbreak management before regulation, width as specified in the EU regulation and width in practical outbreak management after regulation. Numbers in brackets represent the frequency (number of outbreak case reports). Details are given in Appendix S3

| Species | Status | Width in practice before the regulation (m) | Width according to the regulation (m) | Width in practice after the regulation (m) |
|---|---|---|---|---|
| *Insects* | | | | |
| Anoplophora chinensis | A2 | 20 (1), 100 (2) | 100 | 100 (3) |
| Anoplophora glabripennis | A1 | 50 (1), 100 (5), 500 (1) | 100 | 100 (3) |
| Aromia bungii | A1 | | 100 | 100 (1) |
| *Oomycete* | | | | |
| Phytophthora ramorum (EU isolates) | A2 | 1 (1) | 2 | 2 (7) |
| *Insect-vectored pathogenic organisms* | | | | |
| Xylella fastidiosa | A2 | | 100 | 100 (3) |
| Bursaphelenchus xylophilus | A2 | 100 (1), 3,000 (1) | 500 | 3,000 (1) |

**Table 6** Width of the buffer zone in kilometres. Distinction is made between pest status, width in practical outbreak management before regulation, width as specified in the EU regulation and width in practical outbreak management after regulation. Numbers in brackets represent the frequency (number of outbreak case reports). Details are given in Appendix S3

| Species | Status | Width in practice before the regulation (km) | Width according to the regulation (km) | Width in practice after the regulation (km) | Width according to updated regulation (km) | Width in practice after the updated regulation (km) | Width according to (again) updated regulation (km) |
|---|---|---|---|---|---|---|---|
| *Insects* | | | | | | | |
| Anoplophora chinensis | A2 | 1 (1), 2 (1) | ≥ 2 | 2 (3) | | | |
| Anoplophora glabripennis | A1 | 0.5 (1), 1 (5), 2 (2) | ≥ 2 | 0.5 (1), 2 (2) | | | |
| Aromia bungii | A1 | 2 (1), 4 (2) | ≥ 2 | | | | |
| Dryocosmus kuriphilus | A2 | 10 (1) | ≥ 10 | 10 (1), 15 (2) | | | |
| Rhynchophorus ferrugineus | A2 | 10 (2) | ≥ 10 | | | | |
| *Fungi* | | | | | | | |
| Fusarium circinatum | A2 | 1 (1) | ≥ 1 | | | | |
| *Insect-vectored pathogenic organisms* | | | | | | | |
| Xylella fastidiosa | A2 | 10 (5) | ≥ 10 | 10 (3), 11 (1) | ≥ 5 | 1 (1), 5 (4), 10 (1) | ≥ 2.5 |
| Bursaphelenchus xylophilus | A2 | 20 (1) | ≥ 20 | 20 (1) | | | |

of the infested zone was called the containment zone when the aim of the outbreak management was to contain the pest within the infested zone, while it was called the eradication zone when the aim of outbreak management was to eradicate the pest within the infested zone (Appendix S2, ID 82, 83).

### Widths of the buffer zone and clear-cutting zone

The width of the clear-cutting zone was more variable before it was specified in the regulation than after the regulation (Table 5). For the 18 cases in which clear-cutting zones were delimited after a regulation for that species was in place, 17 cases were in accordance with the specified width in the regulation and in one case it was six times wider than the minimum width in the regulation. With one exception, the width of the buffer zone in the regulation was similar to the greatest width that was used in outbreak management before the regulation was put in place (Table 6). The exception was *Aromia bungii* for which the regulated width of the buffer zone was consistent with the smallest width used before regulation in practice.

### Measures in various zones

Different measures were conducted in different zones (Fig. 4). In the infested zone, destruction of all infested plants (78 out of 100 cases) was most frequently applied, followed by destruction of all host plants (42 out of 100 cases). Crop rotation (2 out of 10 insect species) and soil treatments (2 out of 10 insect species) were only done for insects while treatments against vectors (2 out of 13 vectored pathogen species) were used when the outbreak was caused by vectored pathogens. Surveillance was in all cases (92 out of 92) carried out in the buffer zone to verify pest absence. Crop rotation (1 out of 10 insect species), machinery disinfection (1 out of 10 insect species) and chemical treatments (4 out of 10 insect species) were applied only for insects, while treatments against vectors (2 out of 13 pathogen species) and destruction of host plants (1 out of 13 pathogen species) were only used for pathogens. Measures in the infested zone and buffer zone used against insects were more diverse than those used against pathogens. In the infested zone, on average 3.7 (s.e. ± 0.2) different measures were taken for insects and 2.8 (s.e. ± 0.2) for pathogens, and in the buffer zone on average 2.2 (s.e. ± 0.1) different measures were taken for insects compared with 1.4 (s.e. ± 0.1) for pathogens. Other, less frequently applied measures in the infested zone and buffer zone in relation to insects, pathogens and nematodes are listed in Fig. 4.

Measures were frequently used in combination. When destruction of infested plants was applied in the infested zone, it was most often combined with destruction of host plants in that zone (51%). In the infested zone, destruction of volunteer crop plants and machinery disinfection were usually combined (87% of the cases). In the buffer zone, the most commonly applied measure after surveillance was public awareness raising (30% of the cases). When crop rotation was applied in the buffer zone, it was often combined with machinery disinfection (50%). See Table 7 for the interaction between measures in the infested zone and Table 8 for the interaction between measures in the buffer zone.

The combination of zones and their widths and the intensity of measures within each zone varied over time and from one country or place to another, even for one pest, depending on the local situation of pest spread, public acceptance, resources and the experience accumulated over time. See Box 1 for a presentation of two cases that illustrate this point.

**Box 1: Examples showing that for one pest, the zoning strategy differs**

In the Netherlands, the intensity of measures taken to manage the outbreak of *A. glabripennis* in the town of Winterswijk differed from that in an industrial area near Almere (Appendix S2, ID 31, 32). In both cases, the clear-cutting zone had a radius of 100 m. However, the intensity of clear-cutting measures within the 100-m-radius clear-cutting zone was greater in Almere than in Winterswijk. In Almere, all trees with symptoms as well as all host plants were destroyed within a 100-m-radius clear-cutting zone. In Winterswijk, all infested trees and all susceptible trees were eliminated in the first 50 m while in the range of 50–100 m only host plants of at least 2 m in height were destroyed (EPPO

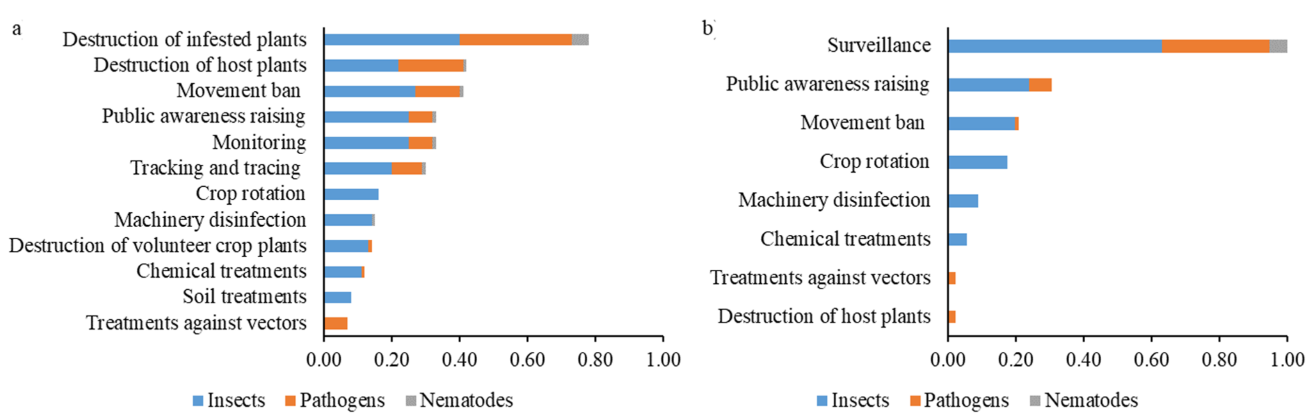



**Fig. 4** Frequency of measures in the infested zone **a** and buffer zone **b** for insects (*blue bars*), pathogens (*orange bars*) and nematodes (*grey bars*). The frequency is calculated by dividing the number of cases with the measure applied for insects, pathogens and nematodes by the number of cases where an infested zone (100 cases) or a buffer zone (92 cases) was delimited

**Table 7** Cross tabulation of measures in the infested zone. Numbers represent frequencies of measures occurring together. Numbers in brackets represent the conditional probability of the measure in a column if the measure in the row is carried out (i.e. the condition). For instance, 40 out of 78 cases with destruction of infested plants also had destruction of host plants. Bold numbers represent the frequency of the most frequent additional measure (columns) if the measure in a row is carried out

| | Destruction of host plants | Movement ban | Public awareness raising | Tracking and tracing | Monitoring | Chemical treatments | Crop rotation | Machinery disinfection | Destruction of volunteer crop plants | Treatment against vectors | Soil treatments | Total cases |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Destruction of infested plants | **40 (0.51)** | 32 (0.41) | 24 (0.31) | 27 (0.35) | 15 (0.19) | 7 (0.09) | 0 (0.00) | 1 (0.01) | 0 (0.00) | 7 (0.09) | 3 (0.04) | 78 |
| Destruction of host plants | | 14 (0.33) | 12 (0.29) | **15 (0.36)** | 7 (0.17) | 2 (0.05) | 0 (0.00) | 0 (0.00) | 1 (0.02) | 1 (0.02) | 1 (0.02) | 42 |
| Movement ban | | | 11 (0.27) | **12 (0.29)** | 9 (0.22) | 7 (0.17) | 7 (0.17) | 6 (0.15) | 5 (0.12) | 7 (0.15) | 7 (0.17) | 41 |
| Public awareness raising | | | | 10 (0.30) | **13 (0.39)** | 3 (0.09) | 8 (0.24) | 8 (0.24) | 8 (0.24) | 2 (0.06) | 2 (0.06) | 33 |
| Tracking and tracing | | | | | **10 (0.33)** | 1 (0.03) | 0 (0.00) | 0 (0.00) | 1 (0.03) | 3 (0.10) | 0 (0.00) | 30 |
| Monitoring | | | | | | 5 (0.15) | **16 (0.48)** | 9 (0.27) | 13 (0.39) | 2 (0.06) | 5 (0.15) | 33 |
| Chemical treatments | | | | | | | **3 (0.25)** | 1 (0.08) | 0 (0.00) | 0 (0.00) | **3 (0.25)** | 12 |
| Crop rotation | | | | | | | | **13 (0.81)** | **13 (0.81)** | 0 (0.00) | 5 (0.31) | 16 |
| Machinery disinfection | | | | | | | | | **13 (0.87)** | 0 (0.00) | 5 (0.33) | 15 |
| Destruction of volunteer crop plants | | | | | | | | | | 0 (0.00) | **5 (0.36)** | 14 |
| Treatment against vectors | | | | | | | | | | | 0 (0.00) | 7 |

The conditional probability is calculated by dividing the number of cases with two measures executed in combination by the total number of cases with the measure in a row

**Table 8** Cross tabulation of measures in the buffer zone. Numbers represent frequencies of measures occurring together. Numbers in brackets represent the conditional probability of the measure in a column if the measure in the row is carried out (i.e. the condition). For instance, 28 out of 92 cases with surveillance also had public awareness raising. Bold numbers represent the frequency of the most frequent additional measure (columns) if the measure in a row is carried out

| | Public awareness raising | Movement ban | Crop rotation | Machinery disinfection | Chemical treatments | Destruction of host plants | Treatment against vectors | Total cases |
|---|---|---|---|---|---|---|---|---|
| Surveillance | **28 (0.30)** | 19 (0.21) | 16 (0.17) | 8 (0.09) | 5 (0.05) | 2 (0.02) | 2 (0.02) | 92 |
| Public awareness raising | | 7 (0.25) | **8 (0.29)** | **8 (0.29)** | 0 (0.00) | 0 (0.00) | 1 (0.04) | 28 |
| Movement ban | | | 0 (0.00) | 0 (0.00) | **2 (0.11)** | 0 (0.00) | 1 (0.05) | 19 |
| Crop rotation | | | | **8 (0.50)** | 2 (0.13) | 0 (0.00) | 0 (0.00) | 16 |
| Machinery disinfection | | | | | 0 (0.00) | 0 (0.00) | 0 (0.00) | 8 |
| Chemical treatments | | | | | | 0 (0.00) | 0 (0.00) | 5 |
| Destruction of host plants | | | | | | | 0 (0.00) | 2 |

The conditional probability is calculated by dividing the number of cases with two measures executed in combination by the total number of cases with the measure in a row

2010, 2012). This is because the outbreak in Winterswijk was much smaller and intensive clear-cutting was much harder to implement in a residential area where the public was more affected.

2-km-wide buffer zones were delimited in 2011 and 2016 to manage *A. bungii* in Rosenheim, Germany. These two zones were merged into a single 4-km-wide buffer zone in 2019 because of expansion of the two outbreaks (Appendix S2, ID 34).

Measures for the control of *X. fastidiosa* have evolved over time as a result of the accumulation of experience with the spread of the disease and also in response to evolving legislation and social pressures (Appendix S2, ID 81, 82, 83). At the first detection of *X. fastidiosa* in Puglia (Italy) in 2013, no demarcated area was defined. However, an eradication programme was launched as required in European Union (2000). An infested zone, buffer zone, eradication zone and surveillance zone were subsequently delimited to eradicate the pest in early 2015. In the infested zone, destruction of infested plants and a movement ban were applied and destruction of host plants was implemented in the outer part of the infested zone, which was the eradication zone. In the buffer zone, surveillance, as well as destruction of host plants within a specific radius around newly detected infested plants, was applied. A surveillance zone was demarcated immediately north of the buffer zone. In the surveillance zone, host plants of insect vectors were treated with insecticide and surveillance was conducted. However, eradication appeared not feasible in Lecce due to the large number of infested hosts, epidemiological characteristics of the pest, various host plant species behaving as a reservoir of the bacterium, and a minimal implementation of the measures due to the public's objection to uprooting trees. Later in 2015, the aim of the outbreak management was changed to containment. Destruction of infested plants was not required anymore in the infested zone, but the outer part of the infested zone was delimited as a containment zone where clearance of infested plants had to be applied to contain the organism within that area while destruction of host plants applied only in a zone with a specific radius within the buffer zone. The infested zone, containment zone and buffer zone were moved northward covering the subsequent outbreaks in Brindisi and Taranto province of Puglia region in 2016 (Fig. 5). An infested zone (including a containment zone), buffer zone and surveillance zone adjacent to the buffer zone were delimited. All known host plants of the European isolates of *X. fastidiosa* within a radius of 100 m of each infested plant in the buffer zone were intended to be destroyed, shredded and treated to prevent further spread of the bacterium, together with insecticide treatments targeted on insect vectors. These measures, limited to infested plants, were also implemented in the containment zone.

## Effects of regulation and infestation size on zoning strategies

The implementation of a harmonized regulation and the size of infestation had a significant effect on the frequency of zones (Fig. 6). The percentage of cases that were delimited with the combination of zones prescribed in regulation differed before and after the regulation ($\chi2=4.51$, df = 1, P = 0.034) showing that outbreak management strategies converged after regulation (5 out of 22 cases). The percentage of cases that was managed with only one delimited zone depended on the infestation size ($\chi2=9.140$, df = 1, $P=0.003$). NPPOs were more prone to delimit only one zone when the infestation size was smaller than 100 $m^2$ (21 out of 61 cases) than when the infestation size was larger than 100 $m^2$ (5 out of 50 cases).

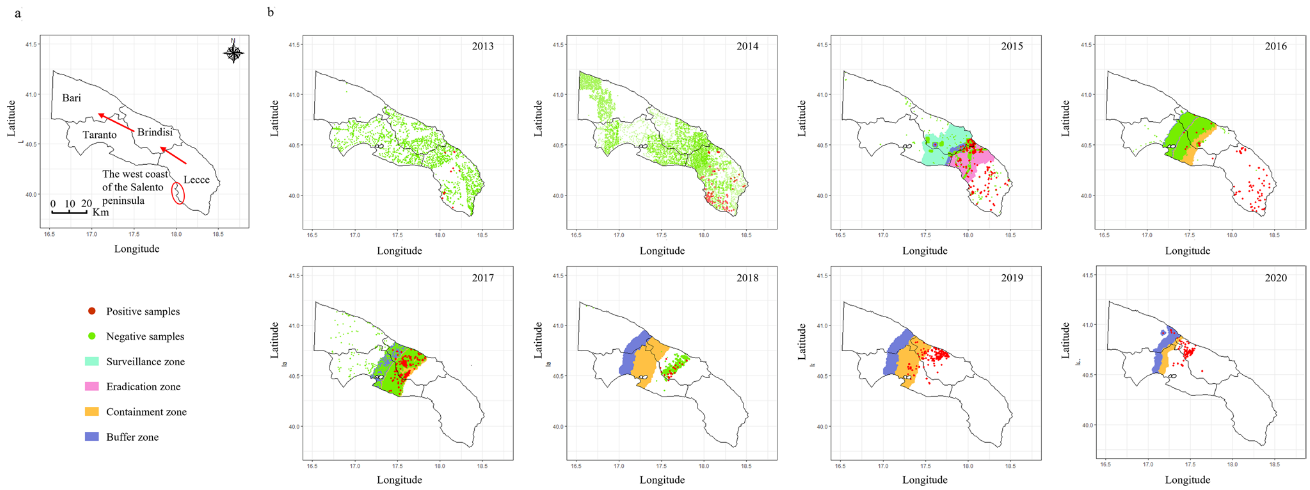



**Fig. 5** **a** Maps of Lecce, Brindisi, Taranto and Bari provinces in Puglia region, Italy. *Red oval* on the west coast of the Salento peninsula indicates where *Xylella fastidiosa* was first detected, *red arrows* indicate the direction of spread of *X. fastidiosa* from the South to the North in Puglia. **b** The detection of positive plants and demarcated zones for managing *X. fastidiosa* in Puglia, Italy from 2013 to 2020 (https://www.emergenzaxylella.it). *Red points* represent positive infection, *green points* represent samples that are tested negative (with data available from 2013 to 2018), *light green area* represents the surveillance zone (2015), *pink area* represents the eradication zone (2015), *ochre area* represents the containment zone (2016–2020) and *blue area* indicates the buffer zone (2015–2020). The infested zone includes the eradication zone or containment zone and extends to the southernmost of Puglia

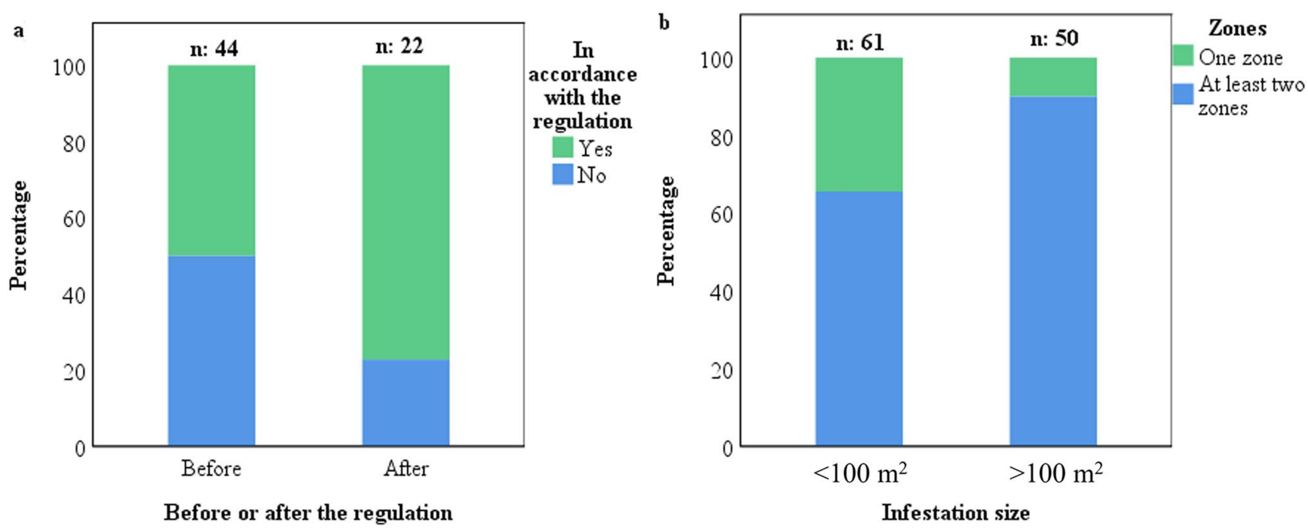



**Fig. 6** **a** Percentage of cases that used the combination of zones as was prescribed in the regulation before and after the regulation; **b** Percentage of cases that were managed with only one delimited zone when the infestation size was smaller or larger than 100 $m^2$. The number above the bars represents the number of cases

## Discussion

The aim of this paper was to review the zoning strategies that are used to manage outbreaks of plant pests in the EU. From reviewing 121 outbreak reports on the EPPO global database, we find that three main zones were delimited in practice: an infested zone, a buffer zone and a clear-cutting zone; other zones could be considered as special cases of one of these three zones. The eradication zone and containment zone were special cases in managing *X. fastidiosa.* The buffer zone and infested zone are adjacent to each other and non-overlapping. The clear-cutting zone is either located inside the infested zone surrounding the infested plants or inside the buffer zone and adjacent to the infested zone, while the containment zone and eradication zone are both inside the infested zone and adjacent to the buffer zone. Zones were used in different combinations, and the variation in zoning strategy used was larger before than after regulation.

Our study shows that most often the infested zone is delimited along with a buffer zone, although substantial variation exists. When the infestation size was small, i.e. there are only a few infested individuals, NPPOs tended to delimit either only an infested zone, a buffer zone or a clear-cutting zone. This is because the NPPO has made the assessment that the pest has not established beyond the infested plants (which are often the primary infestations, i.e. those originating from outside the area). If an NPPO concludes after surveillance that the incursion is isolated and the pest is not established, e.g. the pest is detected in an isolated infested plant, the NPPO might only delimit a buffer zone and apply surveillance measures in the buffer zone around the single infestation after destroying the infested plant. If they consider it is likely that the pest has established locally, even though only one infested plant was detected, they would additionally apply clear-cutting measures around this infested plant to eliminate host plants that may be infested but do not show any symptoms. Using infestation size as indicator to determine which zones to delimit may be useful practice as the likelihood of successful eradication decreases with the size of the outbreak (Pluess et al. 2012a; Tobin et al. 2014). A meta-analysis on outbreaks could possibly identify the optimal combination of zones that should be used in various circumstances, but to the best of our knowledge such an analysis has not been done.

Our study showed a close relationship between regulation and practice. The width of zones that were specified in a regulation was almost always the largest width that was used in managing one of outbreaks prior to the regulation. This is a relatively robust decision that builds on experience gained in outbreak management before regulation. Unfortunately, there were insufficient data to evaluate how the width of the buffer zones evolves with updated regulations.

Most cases implemented buffer zones and clear-cutting zones using the radius that was stipulated as a minimum in the regulation, and only a minority of cases implemented larger buffer zones and clear-cutting zones than was stipulated in the regulation. For example, to manage outbreaks of *X. fastidiosa*, despite a reduction in required width of the buffer zone from 10 to 5 km, allowed by Commission Implementing Regulation (EU) 2020/1201 (European Union 2020), the NPPO in Puglia decided to keep the buffer zone at 10 km because previous experience indicated that 10 km is more effective in slowing pest spread than 5 km. Other evidence suggests that zone widths prescribed by regulations are lower than those needed to achieve eradication. For example, before the abolishment of the quarantine status of *D. virgifera virgifera* in the EU, the results of an individual-based model that simulated the dispersal and mortality of *D. virgifera virgifera* showed that the management of *D. virgifera virgifera* would be improved by increasing the minimum width of the focus zone by 4 km and increasing the width of the safety zone by 45 km, as compared to the regulation (Carrasco et al. 2010). Similarly, a clear-cutting zone with a radius of 500 m, as stipulated in the EU regulation, was estimated to be insufficient to eradicate *B. xylophius* (Robinet et al. 2020). Additionally, four spatial Bayesian hierarchical models were used to evaluate the influence of different barriers in the distribution of *X. fastidiosa* in Alicante, Spain, showing that the minimum buffer zone of 2.5 km established by the regulation (European Union 2020) does not cover the entire area at risk of *X. fastidiosa*. Consequently, the plant health authority implemented an additional band of 10 km surrounding the demarcated area (Cendoya et al. 2022). A spatially explicit simulation model was built to model the control strategy for *X. fastidiosa* in Puglia, showing that increasing the width of the buffer zone decreases the infection risk (White et al. 2017).

Thus, the above modelling studies suggest that improved eradication would be achieved with a wider buffer zone or clear-cutting zone than that prescribed by the regulations. However, the required widths that are calculated to be optimal may not be technically nor socially feasible and compromises may need to be explored. For example, an alternative strategy could be to decrease the width of the clear-cutting zone around the infested plants and increase surveillance surrounding infested zones (Robinet et al. 2020). Alternatively, it could be cost-effective to increase surveillance at the European level and a few studies have been conducted to explore relationship between surveillance and eradication efforts (Bogich et al. 2008; Hauser and McCarthy 2009; Epanchin-Niell et al. 2014; Rout et al. 2014; Yemshanov et al. 2017a, b; Thompson et al. 2018). Increasing surveillance may lead to earlier detections of new incursions and higher detection rates of the targeted pest. As these incursions are more quickly discovered, they will have smaller infestation size and higher likelihood of successful eradication (Demon et al. 2011; Epanchin-Niell et al. 2014; Parnell et al. 2014; Bushaj et al. 2020), possibly leading to lower eradication costs. The fact that most eradication attempts are for regulated pests makes it difficult to 'experiment' with alternative management strategies and to explore the effectiveness of different management options. Modelling could help to explore the effectiveness of different combinations of zones under different circumstances and provide some insights into when which combination of zones is most effective (Cook et al. 2016).

The results of our analysis based on the definition on zones highlight that the most frequently applied measure was different between the infested zone, buffer zone and clear-cutting zone due to the functional difference between zones. In the infested zone, destruction of infested plants and host plants was the most frequently applied measure to eradicate the source of infestation. Surveillance was the most frequently applied measure in the buffer zone to verify that the pest is not spreading outside the infested zone, and take measures otherwise. In the clear-cutting zone, the most frequently applied measure was destruction of host plants to eliminate asymptomatic trees. Applying multiple measures in practice is useful because the success of eradication generally requires the combination of several measures applied on an area-wide basis (Suckling et al. 2016).

Even for the same pest, the zoning strategy changed over time and space. This is the result of the trade-off between the costs and benefits of measures applied in a zone with a particular size, and the changing regulation. Intensive measures were applied against *X. fastidiosa* in Puglia at the frontier of invasion. This strategy is supposed to be effective because the frontier is the area with great infection potential, which should receive greater efforts to eradicate any potential invasions (Lodge et al. 2016). An important lesson with *X. fastidiosa* is that regulations should be flexible enough to cope with the particularities of each outbreak.

Finally, we found that synonyms are often used for the infested zone, buffer zone and clear-cutting zone, but homonyms are used rarely, i.e. in the case of the safety zone (either infested zone or buffer zone) and the focus zone (either infested zone, clear-cutting zone or buffer zone). Inconsistency in naming of different zones hampers the evaluation of the effectiveness of zoning strategies (Pluess et al. 2012a, b). Some case reports could not be used because of high uncertainty about what was done (Fig. 2). A systematic comparison of eradication programmes across countries worldwide is lacking, but it is likely that the eradication procedures are comparable among the countries or regions that follow the IPPC standard (see for example the case of Plum pox virus in Pennsylvania US; Gougherty et al. 2015) and hence could benefit from standardized terminology. This stresses the need for countries to use the term of buffer zone defined in ISPM 5 and to define other terms such as infested zone, and clear-cutting zone explicitly from the perspective of the pest presence, location of the zones in relation to the incursion and the measures taken within a zone. Analyses of past outbreaks and their management are facilitated if authorities report their management using standardized terminology. A map of demarcated zones is an effective tool to communicate the actual zoning approach followed. Finally, it would be advantageous if NPPOs report zoning strategies for non-regulated pests to enable a further analysis of differences in zoning strategies between regulated and non-regulated pests.

## Conclusion

This synthesis demonstrates that three main zones were delimited for management of outbreaks of plant pests in the EU: an **infested zone** where the presence of the specified organism has been confirmed, and which includes all plants showing symptoms caused by the specified organism and, where appropriate, all plants belonging to the same lot at the time of planting (European Union 2015), a **clear-cutting zone** with a specific radius around individual infested plants or around the infested zone where complete clearance of hosts is conducted (European Union 2012b, 2015) and a **buffer zone** with a specific radius beyond the boundary of the infested zone (European Union 2015), aimed to minimize the possibility of spread of the target pest out of the infested zone (ISPM 5, FAO 2021), and which may contain no known infested plants and, where at least surveillance is conducted and/or other phytosanitary measures, e.g. conducting public awareness campaigns, can be included to verify the absence of pest in this area (EPPO 2021b). The combination infested zone + buffer zone was used most frequently. Usually, only one zone was delimited when the infestation size was small. Zoning strategies became less diverse after a pest became regulated because regulations often prescribe the type and a minimum width for zones. The effectiveness of zoning strategies in practice needs to be evaluated, and guidelines on designing cost-effective zoning strategies could be explored by modelling pest spread, spatial allocation of measures and costs.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s10340-023-01591-y.

**Acknowledgements** We thank M. Suffert for her participation in the interviews and her comments on earlier versions of the manuscript.

**Author contributions** WW conceived the idea. HS, WW and JD developed the methodology. HS collected and analysed data and wrote the first draft of the manuscript. MS, RP, DB and AV shared their insight in how management of outbreaks of plant pests is done in practice. All authors contributed to modifying the final manuscript.

**Funding** This study was supported by the China Scholarship Council (China; grant number: 201906350034).

**Data availability** All data generated and analysed during this study are included in this published article and its supplementary information files.

## Declarations

**Conflict of interest** The authors declare that there is no conflict of interest/competing interests.

**Consent for publication** All authors consent to the publication of this manuscript in Journal of Pest Science.

**Ethical approval** This study does not contain any experiments using any animal species that require ethical approval.



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