Global benefits and domestic costs of a cooperative surveillance strategy to control transboundary crop pathogens

Andrea Radici, Davide Martinetti, Daniele Bevacqua

To cite this version:

Andrea Radici, Davide Martinetti, Daniele Bevacqua. Global benefits and domestic costs of a cooperative surveillance strategy to control transboundary crop pathogens. Plants, People, Planet, 2023, 10.1002/ppp3.10379 . hal-04113143

Received: 26 January 2023 | Revised: 12 April 2023 | Accepted: 12 April 2023
DOI: 10.1002/ppp3.10379

Plants People Planet PPP
Open Access

RESEARCH ARTICLE

Global benefits and domestic costs of a cooperative surveillance strategy to control transboundary crop pathogens

Andrea Radici[1] | **Davide Martinetti**[1] | **Daniele Bevacqua**[2]

[1]BioSP UR 546, INRAE, Avignon, France
[2]PSH UR 1115, INRAE, Avignon, France

Correspondence
Davide Martinetti, BioSP UR 546, INRAE, 228 route de l'Aérodrome, CS 40509 Domaine Saint Paul - Site Agroparc, 84914, Avignon, France.
Email: davide.martinetti@inrae.fr

Funding information
French National Research Agency, Grant/Award Number: 20-PCPA-0002; INRAE

Societal Impact Statement

Surveillance of plant pathogens is usually designed according to country boundaries. Benefits of a global surveillance system to tackle long-distance dispersed crop pathogens are unquantified. Here, a 'non-cooperative' and a 'cooperative' strategy are compared in terms of minimizing the surveillance effort to achieve given domestic and global targets. Although a 'cooperative' strategy is always more suitable, impacts of its adoption are not equally distributed among countries. Medium-sized countries in central Europe and Asia would benefit the most from reducing the domestic effort, whereas others would need to deploy more sentinels than they would place in their own interests.

Summary

- Transboundary diseases are extremely complex to control and can cause global socio-economic damage. In the context of crop protection, surveillance strategies are usually designed according to country boundaries, regardless of the spatial scale of the spread of the disease.
- In this study, we investigate the suitability of this scale for surveilling long-distance dispersed pathogens. We use an epidemic network describing worldwide potential transport of *Puccinia graminis*, the causal agent of stem rust of wheat, modelled in a previous work. Based on network properties, we conceive two strategies for prioritizing areas to be monitored for the presence of the disease, either cooperative or each country alone, and we compare their performances in terms of minimizing the effort deployed in achieving given surveillance targets at global and domestic level.
- We find that a cooperative strategy is more efficient at the global scale. However, its adoption implies a heterogeneous geographic distribution of surveillance effort-related costs and benefits. Medium-sized countries in central Europe and Asia would benefit the most; on the other hand, countries placed in important spreading pathways should deploy more surveillance effort than they would place without cooperation. Among the major wheat producers, China is the only country that may have a cost from a cooperative strategy, whereas India, Russia, the United States, France and Ukraine would have the most benefits.

- The acknowledgement of how costs and benefits of a global governance would be shared among countries is needed to gain unanimous support for an international cooperative surveillance system.

KEYWORDS
crop protection, long distance dispersal, network, *Puccinia graminis*, transboundary surveillance

1 | INTRODUCTION

The issue of surveillance of transboundary diseases, hereinafter intended as infectious diseases whose rapid spatial spread is likely to concern more than a country, has recently come in the spotlight due to the Covid-19 pandemic (Chinazzi et al., 2020; Dhama et al., 2020; Mohamed et al., 2020; Soubeyrand et al., 2020). New outbreaks of such diseases (Brockmann & Helbing, 2013; Saunders et al., 2019), as well as biological invasions of alien species (Diagne et al., 2021), are hardly predictable events. They can be shaped by different dissemination pathways (human transportation, commodity shipping, animal vectors or atmospheric agents) and cause socio-economic and health issues. Furthermore, lack, mismatch or delay in the communication of first detection among countries, together with uncoordinated control measures, may lead to inefficient management (Carvajal-Yepes et al., 2019; Thompson et al., 2016). Notably, the threat posed by airborne crop pathogens represents a paradigmatic case of transboundary spread (Corredor-Moreno & Saunders, 2020; Isard et al., 2005; Xing et al., 2020). The risk of large losses in food production due to unexpected outbreaks has prompted researchers and institutions to explore international surveillance systems to timely tackle the diffusion of the most alarming crop pathogens (Carvajal-Yepes et al., 2019; Park et al., 2011). The spatio-temporal persistence of large-scale seasonal movements, such as the well-known *Puccinia* pathway from Mexico to Canada (Aylor, 2003; Brown & Hovmøll, 2002), has recently emerged as a major source of inspiration for devising such innovative surveillance systems (Allen-Sader et al., 2019; Meyer et al., 2017; Radici et al., 2022; Sutrave et al., 2012). In spite of such efforts, standard surveillance of transboundary crop diseases has frequently been performed according to country boundaries, without a cooperative perspective, regardless of the actual scale of spread of the disease, lacking international, and timely, communication of first detections (Carvajal-Yepes et al., 2019; Park et al., 2011; Ristaino et al., 2021). Yet, benefits from a possible general reduction of surveillance effort of a global, cooperative and communicative strategy (Thompson et al., 2016) over a non-cooperative one, that is, each country alone, have never been quantified in the case of long-distance dispersed pathogens.

In this study, we investigate to what extent, and under which conditions, country boundaries represent a suitable scale for surveillance of long-distance dispersed crop pathogens and whether international cooperation would make crop protection more effective. We use stem rust of wheat, caused by *Puccinia graminis*, an airborne fungal pathogen whose spores can be transported over long distances by wind (Levetin, 2015), as a case study. In the majority of wheat-producing countries, the presence of this pathogen has been controlled by the use of resistant cultivars and the eradication of its secondary host, *Berberis vulgaris*, which enables overwintering in temperate regions. This pathogen reappeared in western Europe after several decades of absence (Barnes et al., 2020; Corredor-Moreno & Saunders, 2020; Saunders et al., 2019) and is considered a threat to global food security due to the rapid spread of virulent races through a worldwide distributed host. In a recent article, we retraced its global epidemic network across worldwide wheat-producing countries (Radici et al., 2022). In the present study, we use this epidemic network to conceive two surveillance strategies, a 'non-cooperative' one, representing a within-boundary scenario with no collaboration and communication between countries, and a 'cooperative' one, where countries collaborate surveilling each other and timely communicate the detection of the disease. We compare their performances in terms of surveillance effort needed to achieve given targets both at the global and domestic scales.

2 | MATERIALS AND METHODS

2.1 | The worldwide *Puccinia* epidemic network

In order to evaluate the performances of different surveillance strategies, we used the epidemic networks obtained in a previous study. Here, we present a summary of the methodology proposed there. In Radici et al. (2022), we simulated worldwide transport of *P. graminis* spores among wheat-producing countries, obtaining a time-varying directed and weighted connectivity network $\mathbf{W}$. In $\mathbf{W}$, the 7814 nodes represent $0.5^\circ \times 0.5^\circ$ cells ($\approx 2000\,\mathrm{km}^2$) in wheat-producing countries, whereas edges represent likely air-mass connections among cells, computed at a time resolution of 6 h for the time span 2013–2016. More specifically, each weighted edge w_{ijt} of $\mathbf{W}$ is computed in such a way to account for the likelihood of air-mass trajectories (computed via NOAA's HYSPLIT model; Draxler & Hess, 1998), which potentially disseminate spores from a release node i to an arrival node j at time t. In both i and j, host availability and favourable environmental conditions (for sporulation and/or infection) are determined via a climate-dependent suitability model and validated via a comparison with cropping calendar from the FAO country briefs (FAO, 2021a). Seventy-two-hour trajectories (Meyer et al., 2017) are filtered according to different criteria (rain washout, cumulative UV radiation, flight duration and altitude) to exclude those air-mass movements that are less likely to lead to an effective spore transport event.

We then projected this time-varying epidemic networks in a static, directed and binary design network $\mathbf{W_D}$, generated by considering only recurring connections, that is, occurring (i) at least once a year and (ii) at least three times over the 4-year interval 2013–2016 (i.e. $\geq 75\%$ of the years). Network $\mathbf{W_D}$ identifies only highly likely direct spore dissemination events on a seasonal timescale.

2.2 | Surveillance strategy design

We further considered the problem of establishing a reduced set of *sentinels*, nodes where the presence of the pathogen is systematically monitored (i.e. the surveillance effort), that should guarantee the largest aggregated coverage of the domain (i.e. the surveillance target) and provide an early-warning system for the detection of the pathogens (Radici et al., 2022). First of all, we defined the *coverage* of a sentinel as the set of nodes that points directly towards it, under the assumption that, by monitoring the presence of the pathogen in a sentinel, we can indirectly observe the possible presence in all those nodes that are pointing to it in one step. We leveraged on an iterative heuristic algorithm to determine sub-optimal solutions to the problem of finding the smallest set of sentinels $\mathbf{s_\sigma}$ that guarantees the maximum aggregated coverage (associated with a surveillance target σ).

The iterative heuristic algorithm (or 'Set cover') to determine sub-optimal solutions to the problem of finding the smallest set of sentinels consists in (i) finding the node associated with the largest coverage; (ii) adding this node to the sentinel set $\mathbf{s_\sigma}$, initially empty; (iii) labelling its coverage as surveilled and remove all the edges pointing to it; and (iv) repeating steps i–iii until the proportion of nodes in the aggregated coverage reaches the desired target σ. The optimal set of sentinels $\mathbf{s_\sigma}$ is ranked by growing aggregated coverage. The size of $\mathbf{s_\sigma}$ defines the surveillance effort x_σ.

We designed two surveillance strategies, a 'cooperative' and a 'non-cooperative' one. In the 'cooperative' strategy, the Set cover algorithm was run on all nodes of the network. By contrast, in the 'non-cooperative' strategy, we (i) labelled each node with the country where it is placed and (ii) ran the Set cover algorithm separately for each country by considering only the corresponding sub-block of the network. We thus obtained the optimal sentinel sets $\mathbf{s}^{-\mathbf{T}}_{\boldsymbol{\sigma},\mathbf{c}}$ for each country c, where $^{-T}$ stands for 'without Transboundary edges', ranked by growing aggregated domestic coverage. To compare the performances of the 'cooperative' and 'non-cooperative' strategies, we computed the number of sentinels needed to achieve different global targets (Figure 1).

2.3 | Measuring benefits and costs of cooperation at domestic scale

To investigate how the burden of cooperative surveillance is shared among countries, for each country c, we calculated the number of sentinels $x_{c,\sigma,s}$ needed to achieve a domestic surveillance target of σ under a given strategy s ($s =$ 'cooperative' or 'non-cooperative'). Then, we defined the cost–benefit index $\alpha_{c,\sigma}$ as the ratio between the number of domestic sentinels needed to achieve σ in the 'cooperative' and in the 'non-cooperative' strategy, for a given country c:

$$\alpha_{c,\sigma} = \frac{x_{c,\sigma,s\,=\,cooperative}}{x_{c,\sigma,s\,=\,non-cooperative}}$$

We evaluated it for $\sigma = 1\%, 2\%, \ldots\ 100\%$ and then we computed the average ($\overline{\alpha}_c$) by country. We ascribe to a country c the label of 'CoopBeneficial' if $\overline{\alpha}_c < 1$, 'CoopAdverse' if $\overline{\alpha}_c > 1$ and 'CoopNeutral' if $\overline{\alpha}_c = 1$. After having computed $\overline{\alpha}_c$ by country, we aggregated it by continent weighting each country's contribution by its wheat production (FAO, 2021b) to investigate geographical heterogeneity of benefits and costs of cooperative surveillance.

2.4 | Robustness of the sentinel sets

To assess the temporal robustness of the results to slight changes in the epidemic network, we set up a validation procedure of the performances of the sentinel sets. We recomputed the connectivity network $\mathbf{W}$ on years 2017–2018 and projected it into a validation (directed, binary, static) network $\mathbf{W_V}$, obtained by considering only those connections occurring at least once a year both in 2017 and 2018.

We then recomputed the aggregated coverage and $\alpha_{c,\sigma}$ of the sentinels sets $\mathbf{s_\sigma}$ and $\mathbf{s}^{-\mathbf{T}}_{\boldsymbol{\sigma},\mathbf{c}}$ using network $\mathbf{W_V}$.

3 | RESULTS

Our global epidemic network, together with the applications of the Set cover algorithm, allowed us to identify those sentinels that would best perform to detect disease presence within a certain portion of the network. Note that sentinels might not be included in the network portion that one wants to surveil. For example, if the objective is to monitor the portion of the network corresponding to all wheat-producing regions in Germany, regardless of where the sentinels are placed (the 'cooperative' strategy), the optimal sentinel set would comprise only three domestic sentinels (see Figure 1a). On the other hand, it would be necessary to place six sentinels if surveillance could be provided only by domestic sentinels (the 'non-cooperative' strategy; see Figure 1b), not contributing to transboundary surveillance. Our results indicates that, for a σ of 100%, Germany would benefit from a cooperative strategy as the number of domestic sentinels needed to monitor its territory would pass from 6 to 3, thus meaning a cost–benefit index of $= 3/6 = 0.5$. Indeed, the interpretation of the cost–benefit index is rather straightforward: if $\alpha_{c,\sigma} < 1$, country c requires less sentinels within its borders in the 'cooperative' scenario than in the 'non-cooperative' one for achieving the same surveillance target σ. If $\alpha_{c,\sigma} > 1$, the opposite is true, whereas if $\alpha_{c,\sigma} = 1$, country c needs the same number of sentinels in both the strategies for achieving surveillance target σ.

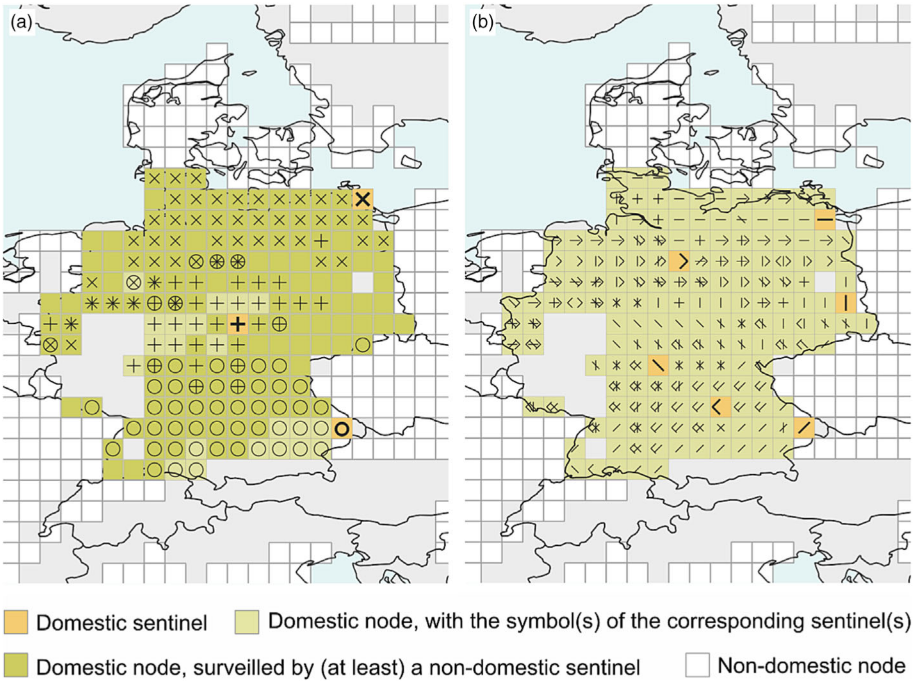

FIGURE 1 A graphic example to compare surveillance strategies of transboundary crop pathogens when the surveillance target is set to $\sigma = 100\,\%$ of the nodes, that is, all nodes of the network points to at least a sentinel. Square cells represent nodes, corresponding to wheat-producing regions, which can be infected by the airborne pathogen *Puccinia graminis*. (a) In the 'cooperative' strategy (i.e. surveillance is optimized as if there were no country borders), three domestic sentinels (orange nodes: **x**, **o**, $+$, surveilling light green cells), in addition to others placed abroad (which surveil dark green nodes), are needed to cover all nodes in Germany. Each node is associated with one or more symbols, each for the sentinel(s) monitoring it. (Note that the sentinel **x** has a domestic cover set which is also surveilled by international sentinels. Yet, in a cooperative framework its role is essential to efficiently surveil nodes out of Germany). (b) In the 'non-cooperative' strategy (i.e. each country optimizes its own surveillance and does not communicate the others the detection of the disease), six domestic sentinels (|, $-$, **/**, ****, **>**, **<**) are needed to surveil German nodes (light green cells). They do not contribute to transboundary surveillance.

3.1 | Global surveillance effort reduction due to cooperation

In a context of non-cooperation between countries, a coverage of half of the worldwide wheat-producing regions (i.e. $\sigma = 50\%$) would be achieved by placing 209 sentinels (Figure 2a), corresponding to 2.7% of the nodes of the global epidemic network. Due to the discrete nature of each coverage, this would correspond to a worldwide target of about $\sigma = 58\%$ (Figure 2a). Note that with the same amount of sentinels, within a 'cooperative' strategy, one would achieve a worldwide coverage of $\sigma = 78\%$. On the other hand, the coverage target of $\sigma = 50\%$ would require only 64 sentinels (Figure 2b). An aggregated coverage of 58% would be obtained with 87 sentinels. If the coverage target were a complete coverage of the worldwide wheat-producing regions (i.e. $\sigma = 100\%$), in a 'cooperative' framework, it would need 1007 sentinels (Figure 2b) and 1148 otherwise.

3.2 | Heterogeneity in the distribution of surveillance effort reduction due to cooperation

Overall, out of 87 countries, 55 (63%) are classified as CoopBeneficial, 23 (27%) as CoopNeutral and nine (10%) as CoopAdverse. In terms of wheat production, around 71% is located in CoopBeneficial countries, 6% in CoopNeutral countries and 23% in CoopAdverse ones (Figure 3). A large variety exists in the cost–benefit index by differentiating countries with large (at least 45 nodes), medium (between 44 and 13 nodes) and small producing regions (12 or less nodes; Figures 3 and S1; see Methods S1). For 47 countries, mainly medium (e.g. Czechia or Uruguay) or large (e.g. India or Russia), the cost–benefit index is always ≤ 1, thus implying an advantage in adopting a 'cooperative' strategy independently of σ. Only four countries (Morocco, Greece, Finland and Nepal) are always discouraged from adopting a 'cooperative' strategy. Great part of the small countries (such as Yemen or New Zealand) display $\alpha_{i,\sigma} = 1$ for any value of σ, for which the two strategies are equivalent. For a few number of large (e.g. the United States, China or Iran) or medium countries (e.g. Moldova or Tunisia), the cost–benefit index is lower or larger than one depending on the value of σ. Their qualification as beneficial or adverse to cooperation depends on the surveillance target.

At the world scale, each continent (except Australia) has at least one CoopBeneficial, one CoopNeutral and one CoopAdverse country (Figure 4a). In North America, countries are typically CoopBeneficial, whereas South America is more balanced. Continental Europe is mainly CoopBeneficial, with some countries (Belgium, Luxembourg, Austria, Slovenia, Croatia, Bosnia and Herzegovina, Albania, North

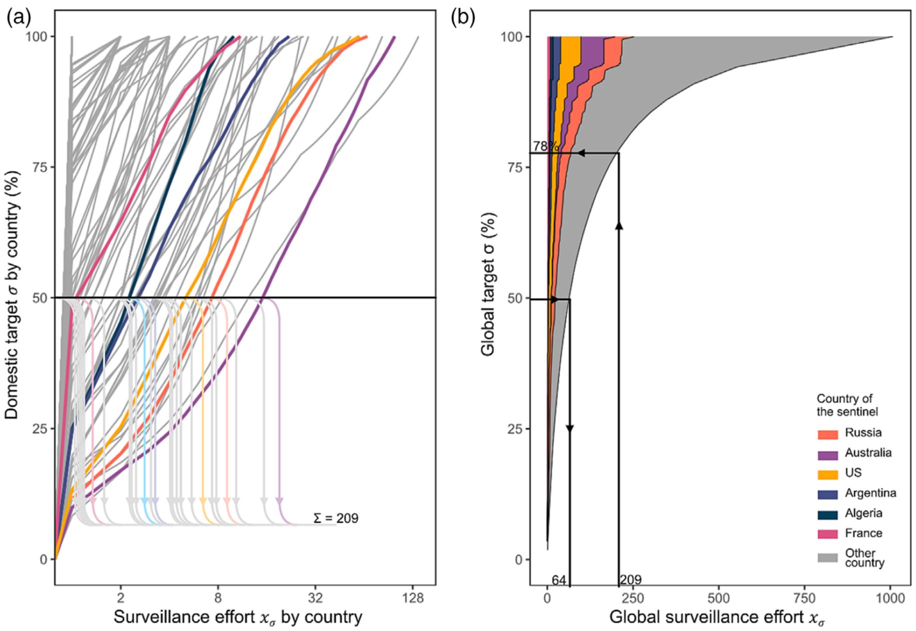

FIGURE 2 Increasing the surveillance target σ (i.e. the proportion of surveilled nodes) requires a surveillance effort x_σ, which varies by country and strategy (i.e. the size of the sentinel set). Each line in panel (a) represents the surveillance effort x_σ (x axis, in $\log_2$ scale) needed by each country to achieve increasing domestic surveillance targets σ (y axis) in the 'non-cooperative' strategy, where each country optimizes its own surveillance strategy for monitoring airborne crop pathogens. We highlighted, via colouring, one representative country for each continent. The intersection of each line with a given surveillance target (e.g. horizontal line at $\sigma = 50\%$) gives the minimum size of the sentinel set for that country (arrows) to reach that given surveillance target. The global effort can be obtained by summing all intersections (209 for $\sigma = 50\%$). Panel (b) shows the global surveillance effort x_σ needed in the 'cooperative' strategy (where we run optimization as if there were no borders) to achieve increasing global surveillance targets σ. In this case, the target $\sigma = 50\%$ is achieved with just 64 sentinels, whereas 209 sentinels ensure a global coverage of 78%.

Macedonia) having $\overline{\alpha}_c = 0$. Finland has the highest $\overline{\alpha}_{\text{Finland}}$ of 1.3, followed by Greece ($\overline{\alpha}_{\text{Greece}} = 1.2$). Asia has a composition similar to Europe, with few CoopAdverse countries (China, Mongolia, Nepal), some isolated CoopNeutral (e.g. Japan) and a majority of CoopBeneficial ones, mainly in inner parts of the continent. Africa is almost entirely CoopNeutral, with the exception of the Maghreb and Tanzania that are CoopBeneficial. Due to geographic isolation, island states such as Australia and New Zealand are CoopNeutral.

3.3 | Robustness of the surveillance strategies

Overall, there is good agreement between the values of $\overline{\alpha}_c$ obtained via the design and the validation network for all countries *c* (correlation coefficient of 0.89; *p*-value $\ll 0.001$; see Methods S1). A visual comparison is also provided in Figures S2–S5.

4 | DISCUSSION

4.1 | From domestic to global cooperative crop protection

As previous research has stressed, the scale of disease management should correspond to that of the spread of the disease of interest, regardless of country boundaries (Thompson et al., 2016). We have collected evidence that, in the case of long-distance dispersed diseases, a 'cooperative' approach allows significant reduction in the surveillance effort needed to achieve a global coverage (-69% and -12% for a global coverage of $\sigma = 50\%$ and 100%, respectively). This outcome agrees with previous studies, which underlined that neglecting long-distance connectivity leads to an underestimation of the disease spread capacity (Jeger et al., 2007).

Despite increasing evidence of a global advantage in cooperative international surveillance, crop surveillance design is still mostly dictated by country boundaries, rather than the actual scale of the pathogen spread (Carvajal-Yepes et al., 2019; Thompson et al., 2016). The mismatch between optimal and actual scale of action affects also other kinds of transboundary natural threats, such as biological invasions by alien species. In this regard, Diagne et al. (2021) recently outlined that invasion-related economic damages are projected to increase in the next decades; one reason behind the inertia in the implementation of international and coordinated protection strategies may lie in the underestimation of the costs by the general public, stakeholders and decision-makers. This may be particularly true in the case of airborne diseases, where the direct observation of their dispersal is actually unfeasible (Barnes et al., 2020; Jordano, 2017), and may discourage consideration by decision-makers.

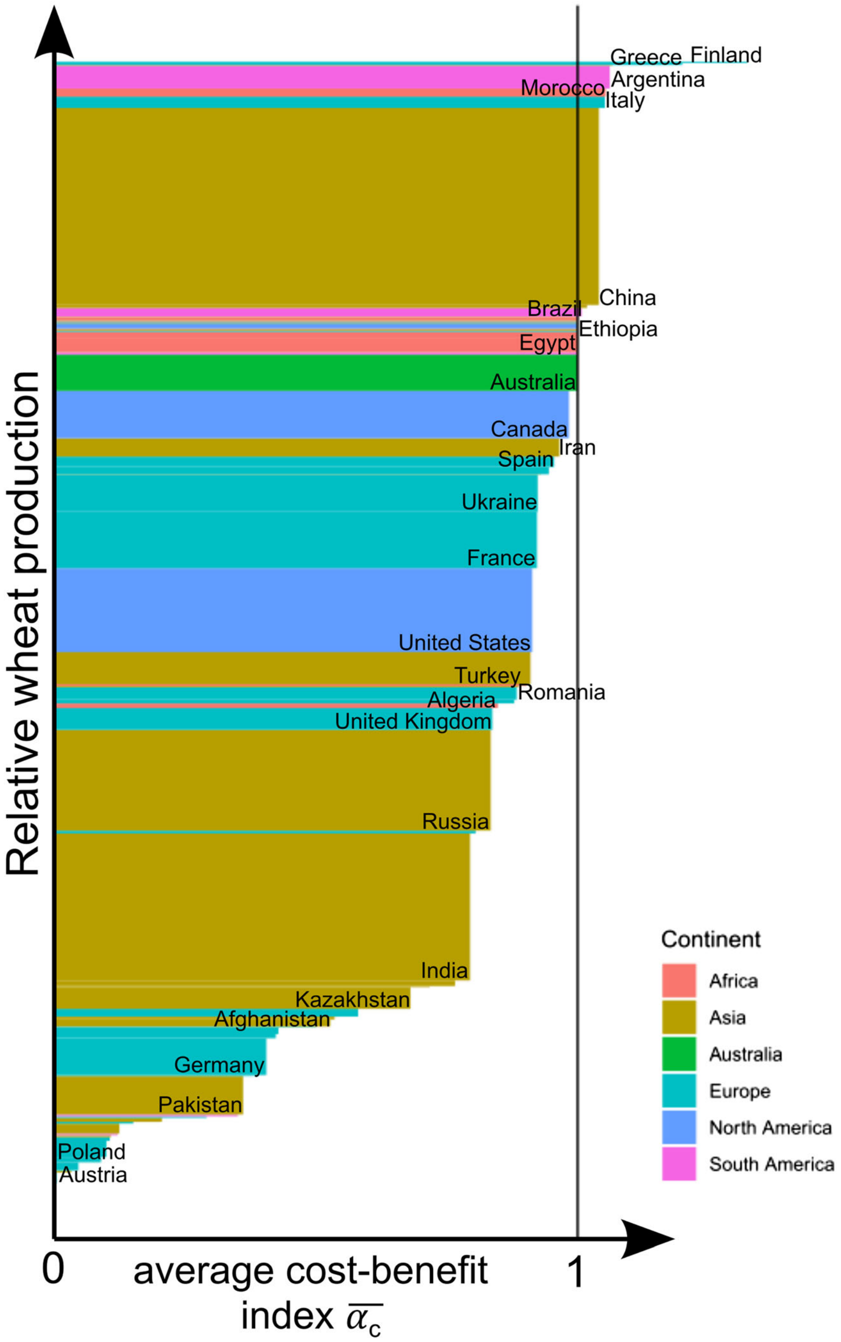

FIGURE 3 Bar chart of the average cost–benefit index $\overline{\alpha}_c$ (x axis) for all wheat-producing countries considered in the study. The cost–benefit index investigates how the burden of cooperative surveillance is shared among countries. Each country is represented by a rectangle where the base is proportional to $\overline{\alpha}_c$ and the height is proportional to wheat production in 2010–2020 (y axis) according to (FAO, 2021b). Countries with $\overline{\alpha}_c < 1$, such as the United States, Russia or India, benefit from cooperative surveillance and are labelled as CoopBeneficial, that is, in a 'cooperative' scenario would need, on average, less sentinels than in a 'non-cooperative' to surveil their wheat production regions against airborne crop pathogen *Puccinia graminis*. On the opposite, $\overline{\alpha}_c > 1$ identifies CoopAdverse countries, such as China. CoopNeutral countries, such as Australia, are indifferent towards cooperation ($\overline{\alpha}_c = 1$).

4.2 | Network thinking in crop surveillance

The use of networks to support crop protection strategies has been largely advocated in recent studies (Garrett et al., 2018; Jeger et al., 2007; Parnell et al., 2017; Shaw & Pautasso, 2014; Sutrave et al., 2012). One advantage of networks is that they are 'asemantic', that is, they can represent whatever relationship, contact or flow mediated by different means (air masses as well as human transportation (e.g. Brockmann & Helbing, 2013) or animal trade (e.g. Bernini et al., 2019) in a topological space, which can correspond to the physical one. In the most simplistic way, crop protection strategies rely on the identification of the nodes of the network that most contribute to spread the disease, or those that, if successfully treated, would reduce the disease size. Other methods rely on the identification of certain recurrent network patterns, where the disease spread is the fastest (Chadès et al., 2011). Concerning surveillance, relevant nodes correspond to those that may allow early disease detection if systematically monitored (Holme, 2017; Neufeld et al., 2018; Sutrave et al., 2012).

Despite the risk of incurring local minima, we used the Set cover algorithm to prioritize nodes to be monitored, that is, sentinels. Set cover iteratively selects the node associated with the highest coverage, solving the otherwise unsolvable Set cover problem in finite time.

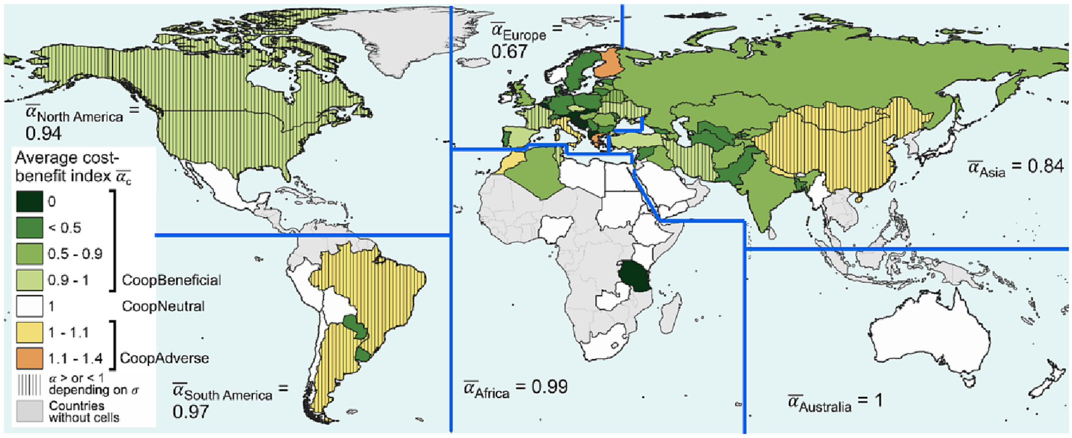

FIGURE 4 Global map of the average cost–benefit index $\overline{\alpha}_c$ by country. Average values by continents (identified by blue lines) weighted by country wheat production 2010–2020 are also displayed. Europe and Asia, and in particular their innermost countries, display the lowest values of $\overline{\alpha}_c$ (they are CoopBeneficial, i.e. they benefit from cooperative surveillance). Insular countries (Australia, New Zealand, Japan) or those with limited wheat-producing surface (mostly African countries) tend to be CoopNeutral. Few countries, often located along or at the end of dissemination pathways (Finland, Argentina, China), are CoopAdverse (i.e. in a cooperative scenario, they would need to deploy more sentinels than they would place in their own interests).

This algorithm only ensures that a node is surveilled by at least one sentinel. A less error-prone procedure may request that nodes are surveilled by at least $n > 1$ sentinels. This would increase the reliability of the sentinel set by reducing the risk of imperfect surveillance (Chadès et al., 2011), but consequently increasing the surveillance effort. Furthermore, in our exercise, we assume that the risk of emergence of new strains (made possible by the alternate host *B. vulgaris*, which allows sexual recombination of *P. graminis*), the costs of surveillance, distribution of resistant varieties and crop management practices are the same in all the nodes. Relaxing these assumptions would ask for a different modelling framework, referable to a multi-constrained and multi-objective problem (such as a multi-dimensional knapsack problem; Kulik & Shachnai, 2010), with increasing complexity of the solution with respect to that of the Set cover algorithm.

This algorithm assumes that sentinel locations are chosen regardless of country borders, although it may not be the case. For these reasons, we named the solution of the above-mentioned algorithm as the 'cooperative' strategy, and we built a second strategy, where surveillance is designed mimicking a more realistic scenario. This strategy, named 'non-cooperative', differs from the previous as the algorithm is carried out each country independently of the others, which means that the Set cover algorithm is solved at the country level. In turn, coverage can be thought as a step-by-step updated version of the in-degree, that is, the number of the edges pointing to a node, penalizing those nodes whose coverage overlaps with that of nodes already labelled as sentinels. Other studies already noted that in-degree (or simply degree for undirected networks) is, as a general rule of thumb, a good proxy of both a good sentinel and a potential disease spreader (Herrera et al., 2016; Holme, 2018).

Moreover, in our work, we proposed a hybrid network and geographical approach, in which metadata are associated with network components: Each node is associated with the label of the corresponding country, and each edge is consequently labelled as 'transboundary' or not. To our knowledge, this is one of the first attempts to compare non-topological surveillance strategies, that is, 'cooperative' and 'non-cooperative', and to quantify the heterogeneity in the allocation of the burden of 'cooperative' surveillance.

Our results thus indicate that the cooperative strategy becomes more valuable when the surveillance target is intermediate. This is mainly due to the fact that this strategy reduces overlapping among coverages. Overlapping is negligible also for the 'non-cooperative' strategy for moderate target of surveillance and becomes relevant for both strategies approaching $\sigma = 100\%$.

4.3 | Sharing benefits and costs of cooperation

From a global perspective, a 'cooperative' strategy is necessarily more efficient compared with a 'non-cooperative' one, because it corresponds to an optimization subjected to fewer constraints. However, it is interesting to quantify how such strategy performs against a 'non-cooperative' strategy at country level, because benefits and burden may not be equally shared; similarly, wheat production is valuable differently according to each country's food system.

We found that medium-sized countries located in an inner continental position, such as in central Europe or central Asia, are associated with the lowest $\overline{\alpha}_c$ values, because they benefit of transboundary potential transport events among a landscape dominated by wheat-producing areas. Insular countries, such as Australia, New Zealand or Japan, having no recurrent edges with other countries, are CoopNeutral. Due to the low presence of wheat, many African and South American countries are CoopNeutral. By contrast, it is more difficult to determine general characteristics for CoopAdverse countries, even keeping in mind that connections are mostly north-eastward in the Northern

Hemisphere and south-westward in the Southern Hemisphere (Radici et al., 2022). Finland and Nepal are small-medium-sized wheat-producing countries, located at the point of arrival of western-eastern European (Zadoks, 1967) and Indian (Brown & Hovmøller, 2002) '*Puccinia* pathways', respectively. Given the relatively small size of their wheat-producing regions, they are forced to assume more sentinels in the benefits of upwind countries, whose food systems are probably much more wheat based, than they would need if left alone. By contrast, Canada, the final destination of the North American pathway, is a large wheat-producing country; hence, it would need several sentinels no matter the strategy. We may suppose that Italy and Greece, due to their location in the middle of the Mediterranean basin, may play as stepping stones for epidemics spreading northward from Africa towards central Europe (Mehta et al., 2007); furthermore, both have relatively low wheat productions; hence, they would need less sentinels if not cooperating. Brazilian and Argentinian large wheat-producing surfaces are located just poleward compared with those of their smaller neighbours (Paraguay and Uruguay, respectively). In the same way, due to the general eastward circulation in the Northern Hemisphere, Chinese wheat-producing regions might act as sink for trajectories from their western neighbours (that are, indeed, CoopBeneficial).

By averaging the cost–benefit index by continent, it is possible to highlight those continents which would benefit the most of a cooperative surveillance. Europe and Asia display the lowest cost–benefit index values (0.6–0.8), whereas for other continents, it is generally around 1. To sum up, the connectivity network of this airborne disease creates a heterogeneous distribution of costs and benefits, but Asia and Europe would certainty take advantage of an international and cooperative surveillance system (Figures 4 and S4).

The heterogeneous geographical distribution of benefits and costs of cooperation in surveillance has already been highlighted by other studies (Bacon et al., 2012) and suggests that a compensating mechanism should be set up to make it acceptable. This compensation mechanism should take into account different costs of surveillance among countries (Augustin et al., 2012). This idea can be borrowed from the socio-economic concept of 'burden sharing' (Sandler & Forbes, 1980; Suhrke, 1998), which is finding application in the management of environmental goods. Differentiate greenhouse gas emissions reduction in the framework of the Conference of the Parties to achieve climate targets (Ringius et al., 2002), as well as in the multi-stakeholder management of marine resources (Bennett et al., 2021), may be two notably example. Furthermore, other fields of crop protection may benefit of a network-based transboundary perspective. For example, the deployment of resistant varieties to both contain pathogens spread and delay resistance overcoming (Rimbaud et al., 2018) is another spatial optimization problem; whether it should be approached at the national or international scale is an interesting issue that can benefit from the approach proposed here.

Although our study tries to push towards a change in the perspective of governance of crop disease surveillance, we believe that proper identification of spatial distribution of costs and benefits can help facilitate international agreement for a global crop epidemic surveillance and gain support of all stakeholders.

AUTHOR CONTRIBUTIONS

Andrea Radici, Davide Martinetti and Daniele Bevacqua designed the research; Andrea Radici and Davide Martinetti performed research; Andrea Radici, Davide Martinetti and Daniele Bevacqua analysed the data; Andrea Radici, Davide Martinetti and Daniele Bevacqua wrote the paper.

ACKNOWLEDGEMENTS

The authors acknowledge the support of funding from the French National Research Agency (ANR) for the BEYOND project (contract no. 20-PCPA-0002) and SuMCrop Sustainable Management of Crop Health Program of INRAE that supported the work of all authors. We thank prof. Nik J. Cunniffe for valuable suggestions.

CONFLICT OF INTEREST STATEMENT

The authors have no competing interests.

DATA AVAILABILITY STATEMENT

The code that supports the findings of this study is available at the repository in https://github.com/radiciandrea/PgraminisTransboundary.git.

ORCID

Andrea Radici https://orcid.org/0000-0001-5852-0015

REFERENCES

Allen-Sader, C., Thurston, W., Meyer, M., Nure, E., Bacha, N., Alemayehu, Y., Stutt, R. O. J. H., Safka, D., Craig, A. P., Derso, E., Burgin, L. E., Millington, S. C., Hort, M. C., Hodson, D. P., & Gilligan, C. A. (2019). An early warning system to predict and mitigate wheat rust diseases in Ethiopia. *Environmental Research Letters*, *14*(11), 115004. https://doi.org/10.1088/1748-9326/ab4034

Augustin, S., Boonham, N., De Kogel, W. J., Donner, P., Faccoli, M., Lees, D. C., Marini, L., Mori, N., Toffolo, E. P., Quilici, S., Roques, A., Yart, A., & Battisti, A. (2012). A review of pest surveillance techniques for detecting quarantine pests in Europe. *EPPO Bulletin*, *42*(3), 515–551. https://doi.org/10.1111/epp.2600

Aylor, D. E. (2003). Spread of plant disease on a continental scale: Role of aerial dispersal of pathogens. *Ecology*, *84*(8), 1989–1997. https://doi.org/10.1890/01-0619

Bacon, S. J., Bacher, S., & Aebi, A. (2012). Gaps in border controls are related to quarantine alien insect invasions in Europe. *PLoS ONE*, *7*(10), e47689. https://doi.org/10.1371/journal.pone.0047689

Barnes, G., Saunders, D. G. O., & Williamson, T. (2020). Banishing barberry: The history of Berberis vulgaris prevalence and wheat stem rust incidence across Britain. *Plant Pathology*, *69*(7), 1193–1202. https://doi.org/10.1111/ppa.13231

Bennett, N. J., Blythe, J., White, C. S., & Campero, C. (2021). Blue growth and blue justice: Ten risks and solutions for the ocean economy. *Marine Policy*, *125*, 104387. https://doi.org/10.1016/j.marpol.2020.104387

Bernini, A., Bolzoni, L., & Casagrandi, R. (2019). When resolution does matter: Modelling indirect contacts in dairy farms at different levels of detail. *PLoS ONE*, *14*(10), e0223652. https://doi.org/10.1371/journal.pone.0223652

Brockmann, D., & Helbing, D. (2013). The hidden geometry of complex, network-driven contagion phenomena. *Science*, *342*(6164), 1337–1342. https://doi.org/10.1126/science.1245200

Brown, J. K. M., & Hovmøll, M. S. (2002). Aerial dispersal of pathogens on the global and continental scales and its impact on plant disease. *Science*, *297*(5581), 537–541. https://doi.org/10.1126/science.1072678

Brown, J. K. M., & Hovmøller, M. S. (2002). Aerial dispersal of pathogens on the global and continental scales and its impact on plant disease. *Science*, *297*(5581), 537–541. https://doi.org/10.1126/science.1072678

Carvajal-Yepes, M., Cardwell, K., Nelson, A., Garrett, K. A., Giovani, B., Saunders, D. G. O., Kamoun, S., Legg, J. P., Verdier, V., Lessel, J., Neher, R. A., Day, R., Pardey, P., Gullino, M. L., Records, A. R., Bextine, B., Leach, J. E., Staiger, S., & Tohme, J. (2019). A global surveillance system for crop diseases. *Science*, *364*(6447), 1237–1239. https://doi.org/10.1126/science.aaw1572

Chadès, I., Martin, T. G., Nicol, S., Burgman, M. A., Possingham, H. P., & Buckley, Y. M. (2011). General rules for managing and surveying networks of pests, diseases, and endangered species. *Proceedings of the National Academy of Sciences*, *108*(20), 8323–8328. https://doi.org/10.1073/pnas.1016846108

Chinazzi, M., Davis, J. T., Ajelli, M., Gioannini, C., Litvinova, M., Merler, S., Piontti, A. P. Y., Mu, K., Rossi, L., Sun, K., Viboud, C., Xiong, X., Yu, H., Halloran, M. E., Longini, I. M. Jr., & Vespignani, A. (2020). The effect of travel restrictions on the spread of the 2019 novel coronavirus (COVID-19) outbreak. *Science*, *368*(6489), 395–400. https://doi.org/10.1126/science.aba9757

Corredor-Moreno, P., & Saunders, D. G. O. (2020). Expecting the unexpected: Factors influencing the emergence of fungal and oomycete plant pathogens. *New Phytologist*, *225*(1), 118–125. https://doi.org/10.1111/nph.16007

Dhama, K., Khan, S., Tiwari, R., Sircar, S., Bhat, S., Malik, Y. S., Singh, K. P., Chaicumpa, W., Bonilla-Aldana, D. K., & Rodriguez-Morales, A. J. (2020). Coronavirus disease 2019–COVID-19. *Clinical Microbiology Reviews*, *33*(4), e00028-20. https://doi.org/10.1128/CMR.00028-20

Diagne, C., Leroy, B., Vaissière, A.-C., Gozlan, R. E., Roiz, D., Jarić, I., Salles, J.-M., Bradshaw, C. J. A., & Courchamp, F. (2021). High and rising economic costs of biological invasions worldwide. *Nature*, *592*(7855), 571–576. https://doi.org/10.1038/s41586-021-03405-6

Draxler, R. R., & Hess, G. D. (1998). An overview of the HYSPLIT_4 modelling system for trajectories, dispersion and deposition. *Australian Meteorological Magazine*, *47*(4), 295–308.

FAO. (2021a). FAO - Country brief.

FAO. (2021b). *World food and agriculture—Statistical yearbook 2021*. World Food and Agriculture-Statistical Yearbook. FAO. https://doi.org/10.4060/cb4477en

Garrett, K. A., Alcalá-Briseño, R. I., Andersen, K. F., Buddenhagen, C. E., Choudhury, R. A., Fulton, J. C., Nopsa, J. F. H., Poudel, R., & Xing, Y. (2018). Network analysis: A systems framework to address grand challenges in plant pathology. *Annual Review of Phytopathology*, *56*, 559–580. https://doi.org/10.1146/annurev-phyto-080516-035326

Herrera, J. L., Srinivasan, R., Brownstein, J. S., Galvani, A. P., & Meyers, L. A. (2016). Disease surveillance on complex social networks. *PLoS Computational Biology*, *12*(7), e1004928. https://doi.org/10.1371/journal.pcbi.1004928

Holme, P. (2017). Three faces of node importance in network epidemiology: Exact results for small graphs. *Physical Review E*, *96*(6), 062305. https://doi.org/10.1103/PhysRevE.96.062305

Holme, P. (2018). Objective measures for sentinel surveillance in network epidemiology. *Physical Review E*, *98*(2), 22313. https://doi.org/10.1103/PhysRevE.98.022313

Isard, S. A., Gage, S. H., Comtois, P., & Russo, J. M. (2005). Principles of the atmospheric pathway for invasive species applied to soybean rust. *Bioscience*, *55*(10), 851–861. https://doi.org/10.1641/0006-3568(2005)055[0851:POTAPF]2.0.CO;2

Jeger, M. J., Pautasso, M., Holdenrieder, O., & Shaw, M. W. (2007). Modelling disease spread and control in networks: Implications for plant sciences. *New Phytologist*, *174*, 279–297. https://doi.org/10.1111/j.1469-8137.2007.02028.x

Jordano, P. (2017). What is long-distance dispersal? And a taxonomy of dispersal events. *Journal of Ecology*, *105*(1), 75–84. https://doi.org/10.1111/1365-2745.12690

Kulik, A., & Shachnai, H. (2010). There is no EPTAS for two-dimensional knapsack. *Information Processing Letters*, *110*(16), 707–710. https://doi.org/10.1016/j.ipl.2010.05.031

Levetin, E. (2015). Aerobiology of agricultural pathogens. In *Manual of environmental microbiology* (pp. 3.2.8-1–3.2.8-20). ASM Press. https://doi.org/10.1128/9781555818821.ch3.2.8

Mehta, S. V., Haight, R. G., Homans, F. R., Polasky, S., & Venette, R. C. (2007). Optimal detection and control strategies for invasive species management. *Ecological Economics*, *61*(2–3), 237–245. https://doi.org/10.1016/j.ecolecon.2006.10.024

Meyer, M., Cox, J. A., Hitchings, M. D. T., Burgin, L., Hort, M. C., Hodson, D. P., & Gilligan, C. A. (2017). Quantifying airborne dispersal routes of pathogens over continents to safeguard global wheat supply. *Nature Plants*, *3*(10), 780–786. https://doi.org/10.1038/s41477-017-0017-5

Mohamed, K., Rodríguez-Román, E., Rahmani, F., Zhang, H., Ivanovska, M., Makka, S. A., Joya, M., Makuku, R., Islam, M. S., Radwan, N., Rahmah, L., Goda, R., Abarikwu, S. O., Shaw, M., Zoghi, S., Irtsyan, S., Ling, I., Cseprekal, O., Faten, A.-B., … Rezaei, N. (2020). Borderless collaboration is needed for COVID-19—A disease that knows no borders. *Infection Control and Hospital Epidemiology*, *41*(10), 1245–1246.

Neufeld, K. N., Keinath, A. P., Gugino, B. K., McGrath, M. T., Sikora, E. J., Miller, S. A., Ivey, M. L., Langston, D. B., Dutta, B., Keever, T., Sims, A., & Ojiambo, P. S. (2018). Predicting the risk of cucurbit downy mildew in the eastern United States using an integrated aerobiological model. *International Journal of Biometeorology*, *62*(4), 655–668. https://doi.org/10.1007/s00484-017-1474-2

Park, R., Fetch, T., Hodson, D., Jin, Y., Nazari, K., Prashar, M., & Pretorius, Z. (2011). International surveillance of wheat rust pathogens: Progress and challenges. *Euphytica*, *179*(1), 109–117. https://doi.org/10.1007/s10681-011-0375-4

Parnell, S., van den Bosch, F., Gottwald, T., & Gilligan, C. A. (2017). Surveillance to inform control of emerging plant diseases: An epidemiological perspective. *Annual Review of Phytopathology*, *55*, 591–610. https://doi.org/10.1146/annurev-phyto-080516-035334

Radici, A., Martinetti, D., & Bevacqua, D. (2022). Early-detection surveillance for stem rust of wheat: Insights from a global epidemic network based on airborne connectivity and host phenology. *Environmental Research Letters*, *17*, 064045. https://doi.org/10.1088/1748-9326/ac73aa

Rimbaud, L., Papaïx, J., Rey, J. F., Barrett, L. G., & Thrall, P. H. (2018). Assessing the durability and efficiency of landscape-based strategies to deploy plant resistance to pathogens. *PLoS Computational Biology*, *14*, e1006067. https://doi.org/10.1371/journal.pcbi.1006067

Ringius, L., Torvanger, A., & Underdal, A. (2002). Burden sharing and fairness principles in international climate policy. *International Environmental Agreements*, *2*(1), 1–22. https://doi.org/10.1023/A:1015041613785

Ristaino, J. B., Anderson, P. K., Bebber, D. P., Brauman, K. A., & Cunniffe, N. J. (2021). The persistent threat of emerging plant disease pandemics to global food security. *Agricultural Sciences*, *118*(23), 1–9. https://doi.org/10.1073/pnas.2022239118

Sandler, T., & Forbes, J. F. (1980). Burden sharing, strategy, and the design of NATO. *Economic Inquiry*, *18*(3), 425–444. https://doi.org/10.1111/j.1465-7295.1980.tb00588.x

Saunders, D. G. O., Pretorius, Z. A., & Hovmøller, M. S. (2019). Tackling the re-emergence of wheat stem rust in Western Europe. *Communications Biology*, *2*(1), 51. https://doi.org/10.1038/s42003-019-0294-9

Shaw, M. W., & Pautasso, M. (2014). Networks and plant disease management: Concepts and applications. *Annual Review of Phytopathology*, *52*, 477–493. https://doi.org/10.1146/annurev-phyto-102313-050229

Soubeyrand, S., Demongeot, J., & Roques, L. (2020). Towards unified and real-time analyses of outbreaks at country-level during pandemics. *One Health*, *11*, 100187. https://doi.org/10.1016/j.onehlt.2020.100187

Suhrke, A. (1998). Burden-sharing during refugee emergencies: The logic of collective versus national action. *Journal of Refugee Studies*, *11*(4), 396–415. https://doi.org/10.1093/jrs/11.4.396

Sutrave, S., Scoglio, C., Isard, S. A., Hutchinson, J. M. S., & Garrett, K. A. (2012). Identifying highly connected counties compensates for resource limitations when evaluating national spread of an invasive pathogen. *PLoS ONE*, *7*(6), e37793. https://doi.org/10.1371/journal.pone.0037793

Thompson, R. N., Cobb, R. C., Gilligan, C. A., & Cunniffe, N. J. (2016). Management of invading pathogens should be informed by epidemiology rather than administrative boundaries. *Ecological Modelling*, *324*, 28–32. https://doi.org/10.1016/j.ecolmodel.2015.12.014

Xing, Y., Hernandez Nopsa, J. F., Andersen, K. F., Andrade-Piedra, J. L., Beed, F. D., Blomme, G., Carvajal-Yepes, M., Coyne, D. L., Cuellar, W. J., Forbes, G. A., Kreuze, J. F., Kroschel, J., Kumar, P. L., Legg, J. P., Parker, M., Schulte-Geldermann, E., Sharma, K., & Garrett, K. A. (2020). Global cropland connectivity: A risk factor for invasion and saturation by emerging pathogens and pests. *Bioscience*, *70*(9), 744–758. https://doi.org/10.1093/biosci/biaa067

Zadoks, J. C. (1967). Internationale verspreiding van schimmels. *Netherlands Journal of Plant Pathology*, *73*(1 Supplement), 61–80. https://doi.org/10.1007/BF01974423

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Radici, A., Martinetti, D., & Bevacqua, D. (2023). Global benefits and domestic costs of a cooperative surveillance strategy to control transboundary crop pathogens. *Plants, People, Planet*, 1–10. https://doi.org/10.1002/ppp3.10379