Food Sec.
DOI 10.1007/s12571-009-0014-2

ORIGINAL PAPER

Plant pathogens as agroterrorist weapons: assessment of the threat for European agriculture and forestry

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Received: 26 November 2008 / Accepted: 3 February 2009

Abstract Malevolent use of plant pathogens in an act of agroterrorism represents a potential threat for European agriculture and forestry. We investigated the risk of agroterrorism *sensu lato*, which is raising debates among the community of plant pathologists. In the absence of a previous unambiguous definition of agroterrorism we characterized the risk for Europe by taking into account the multiplicity of the threat, of the perpetrator's objectives, and of potential *modus operandi*. To this end, we have applied a three-step methodology involving: (1) the building of a list of candidate pathogens, (2) a scenario-based exploration of potential agroterrorist acts, and (3) the design of a risk evaluation scheme (RES), derived from the standard pest risk analysis (PRA). We adopted a congruent risk assessment strategy consisting of coupling the foresight exercise (assignment of nine key pathogens extracted from the list to nine scenarios and comparison of different intrinsic criteria) to the analytical assessment (application of the RES to the nine key pathogens and qualitative analysis resulting in a pentagonal star plot representing risk profiles). Analysis was performed by non-experts on the selected diseases, and thus enabled a comparison between crops or pathogens on the basis of the characterization of the threat. The risk, considered in its hybrid dimension (both factual because it refers to crop protection and an effective stake, and also irrational because it refers to bioterrorism, a vague and unobservable concept) was characterized exhaustively for the selected plant pathogens and the success of a malevolent act appeared to be much more uncertain than believed. However, agroterrorism should be considered as a plausible threat, potentially more important by the consequences of the securitization of the concept, which could imply disruption of regulations and trade, than by direct damaging consequences on European crops. There is probably not a single short-list of threatening pathogens: different pathogens would be most threatening for different purposes, for different perpetrators, and for different target crops.

Keywords Agroterrorism · Anti-crop bioweapons, Crop biosecurity · Foresight · Plant pathogens · Risk assessment

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Introduction

Crop biosecurity, defined as "protecting a state from invasive plant pathogens" (Brasier 2008) is mostly assured by regulations and quarantine measures. The International Plant Protection Convention (IPPC 2004) has in its charge the global harmonization of phytosanitary measures set up

Published online: 11 March 2009

by National Plant Protection Organisations to prevent accidental introductions of invasive exotic plant pests (Schrader and Unger 2003). Regional Plant Protection Organisations, such as the European and Mediterranean Plant Protection Organisation (EPPO 2007), acting as a regional umbrella organisation, aim at improving the harmonization of quarantine protocols. While most exotic invasive plant pests have been either accidentally introduced or passively spread by wind currents, little attention has been paid until recently to the possible, deliberate use of plant pathogens as agroterrorist weapons against crops and forests (Anderson et al. 2004; Desprez-Loustau et al. 2007). Excluding attacks against livestock and wildlife, we will further consider agroterrorism *sensu lato* as the intentional use, as well as the threat or simulation of use of plant pathogens by any individual or group in order to cause direct damage to crops or forests, or to indirectly affect the agricultural sector.

Agroterrorism is not a new issue. For ages, wars have targeted agriculture, mostly by trashing or burning crops and forests, as a means of depriving the enemy of food supply, repel colonists or subjugate rebel populations. More recently, biological anti-crop warfare has been state-sponsored in some of the biggest European countries between 1920 and 1940. Around the Second World War, the main belligerent countries developed research programmes on biological anti-crop agents targeting staple crops, for instance potatoes (with late blight caused by the Oomycete *Phytophthora infestans* and the Colorado potato beetle, *Leptinotarsa decemlineata*) and rice (with brown spot and rice blast, caused by the fungi *Cochliobolus miyabeanus* and *Magnaporthe grisea*, respectively) (Table 1; Madden and Wheelis 2003; Suffert 2003). After the Second World War, several countries continued to conduct research on plant pathogens as anti-crop weapons. The main researched agents were *Puccinia graminis* f.sp. *tritici*, the cause of wheat black rust (Table 1; Line and Griffith 2001), *M. grisea* and *P. infestans* (Table 1; Madden and Wheelis 2003). While the countries that signed the Biological and Toxin Weapons Convention (BTWC) in 1972 officially stopped their biological warfare programs, a new cycle of concern over the possible use of biological anti-crop weapons began in the late 1980s, based on the knowledge that several "rogue" countries were trying to acquire such weapons. Following the First Gulf War, United Nations Special Commission's inspections have revealed that Iraq had expressed an interest in acquiring the military capacity to destroy Iranian crops and that progress had been made with regard to research and development in the weaponization of wheat smut fungi (*Tilletia caries* and *T. tritici*) and aflatoxin-producing strains of the fungus *Aspergillus* (Table 1; Whitby 2002). Additionally, there have been sporadic, unverified allegations that states or militant organizations have either used plant pathogens against crops or threatened to use them (Table 1; Junior 2006; Zilinskas 1999). More recently, evidence found in caves in Afghanistan suggested interest by Islamic militants in the weaponization of wheat rust (Fletcher et al. 2006). Unlikely allegation of deliberate introduction of the western corn rootworm (*Diabrotica virgifera*) in European maize fields in the 1990s could not be completely rejected since population genetics demonstrated the occurrence of multiple transatlantic introductions of the pest (Table 1; Miller et al. 2005). In the 1990s, the United Nations Drug Control Program supported anti-coca and anti-poppy programs in Andean and Central Asian countries, respectively (Table 1; Jelsma 2001). Strains of *Fusarium oxysporum* f.sp. *erythroxyli* (Connick et al. 1998) and *Pleospora papaveracea* (O'Neill et al. 2000) with increased pathogenicity have been selected but were officially never used. The status of these biocontrol agents as biowarfare agents is evidently controversial (Suffert et al. 2008).

Awareness for biosecurity has increased over the last decade owing to growing trade, travel, transportation, and tourism, the "four T's" components of globalization (Waage and Mumford 2007). A relatively minor issue until the last decade, agroterrorism emerged in the scientific literature after 1997 (Suffert et al. 2008). According to Ole Wæver's securitization theory, crop biosecurity and agroterrorism should be considered as "securitized" issues (Buzan et al. 1998). They have become specific fields of research, with a corpus of dedicated articles (e.g., Cupp et al. 2004; Byrne 2007; Khetarpal and Gupta 2007), journals (e.g., "International Journal of Rural Crime", and "Biosecurity and Bioterrorism: Biodefense Strategy, Practice, and Science"), reviews (e.g., Madden and Wheelis 2003; Suffert 2003), textbooks (e.g., Whitby 2002; Gullino et al. 2008) and conferences (e.g., the symposium on "Plant Pathology's role in anti-crop bioterrorism and food security" held by the American Phytopathological Society in 1999, and the annual "International Symposium of Agroterrorism" held since 2005 in the USA).

Agroterrorism as warfare has been deemed "low-tech, high impact" (Wheelis et al. 2002). Only a few methods aimed at a comprehensive assessment of agroterrorism have been proposed (Madden and Wheelis 2003; Schaad et al. 2006). In a previous article, Latxague et al. (2007) have set up a three-step methodology for assessing this risk in Europe involving: (1) the building of a list of candidate pathogens, (2) a scenario-based investigation of potential agroterrorist acts, and (3) the design of a risk assessment scheme. Since this methodology remained to be tested with "real" cases, the objective of the present article is to apply this methodology to potential, worthy of belief, cases of agroterrorism, and then to discuss the relevance of agroterrorism as a scientific issue regards to the results obtained for the risk assessment of selected plant pathogens.

Table 1 Reports of agroterrorist threats *sensu lato* in the 20th century (after Suffert et al. 2008)

Plant pathogens	Target crop	Year	Target area	Origin[a]	Type of acts[b]	Threat evaluation[c]	References
Puccinia triticina	Wheat	1950	USA	Soviet Union	BW2	++	Whitby 2002
		1950	Soviet Union	US	BW2	++	
		2000	USA, Europe	Afghanistan (al-Qaeda)	BT1	+	Fletcher et al. 2006
Puccinia graminis f.sp. *tritici*	Wheat	1950	USA	Soviet Union	BW2	++	Line and Griffith 2001
		1950	Korea	US	BW2	++	Whitby 2002
Tilletia tritici	Wheat	1980	Iran	Iraq	BW2	++	Whitby 2002
Tilletia laevis	Wheat	1980	Iran	Iraq	BW2	++	Whitby 2002
Aspergillus sp. (aflatoxin)	Wheat	1980	Iran	Iraq	BW2, BT1	+	Whitby 2002
Cochliobolus miyabeanus	Rice	1940	Japan	USA	BW2	++	Madden and Wheelis 2003
Magnaporthe grisea	Rice	1940	Japan	USA	BW2	++	Madden and Wheelis 2003
		1940	China	Japan	BW2	++	
		1950	?	Soviet Union	BW2	+	
Phytophthora infestans	Potato	1940	Germany	France	BW2	++	Madden and Wheelis 2003
		1950	?	USA, Canada	BW2	++	Suffert 2003
		1950	?	Soviet Union	BW2	++	
Leptinotarsa decemlineata	Potato	1940	France	Germany	BW2	+	Madden and Wheelis 2003, Suffert 2003
		1940	Germany	UK	BW2	+	
Puccinia melanocephala	Sugarcane	1970	Cuba	USA	BW2	−	Zilinskas 1999
Peronospora hyosciami f.sp. *tabacina*	Tobacco	1970	Cuba	USA	BW2	−	Zilinskas 1999
Hemileia vastatrix	Coffee	1950	Guatemala	USA	BW2	−	Suffert et al. 2008
Crinipellis perniciosa	Cacao	1980	Brazil	?	BW2	–	Junior 2006
Diabrotica virgifera	Maize	2000	Europe	?	BC3	–	Miller et al. 2005, Suffert et al. 2008
Pleospora papaveracea	Opium poppy	1990	Central Asia (Afghanistan)	UNDCP [4], US, UK, Uzbekistan	BW3	++	Jelsma 2001
Fusarium oxysporum f.sp. *erythroxyli*	Coca	2000	Andean Countries (Columbia)	US, Columbia	BW3	++	Jelsma 2001
Melampsora larici-populina	Larch	1990	Europe (France, UK)	Eco-warriors	BT2	−	Suffert et al. 2008

[a] Countries considered as potential state-sponsors (or harboring perpetrators) known or suspected to have been involved in anti-crop programs or agroterrorist acts

[b] *BW* biowarfare, *BT* bioterrorism, *BC* biocrime (see Table 2)

[c] ++ Established threat (officially demonstrated), + probable threat (with limited evidence), − unverified, alleged threat (without significant evidence)

[d] United Nations International Drug Control Program

Methods

We present here only a brief outline of the rationale of the methodology developed by Latxague et al. (2007). In a first step (1), a list of 50 candidate pathogens representing potential agroterrorist threats to the European agriculture and forest was compiled. This list was delivered to the European Commission at the end of the EU project "CropBioterror" and kept confidential for security reasons. It includes not only nonindigenous and quarantine pathogens, but also endemic pathogens with specific characteristics such as mycotoxinogenic ability, high potential of mutation and hybridization and records of highly pathogenic exotic strains. In a second step (2), three kinds of acts were considered (international, state-sponsored biowarfare; non-governmental bioterrorism; and individual or corporate biocrime) and their socio-economical consequences characterized by a "foresight" approach, which consists in carrying explorative studies developing views of future options, and then choosing between them (Major et al. 2001). In a third step (3), the standard pest risk analysis (PRA) scheme, originally used to decide whether an organism should be listed on quarantine lists (EPPO 2007), was dramatically modified into a risk evaluation scheme (RES) to account for the specificity of the agroterrorist threat.

Here, nine different, non-overlapping scenarios of agroterrorist attacks were developed considering a key pathogen taken from the aforementioned list of 50 candidate pathogens, combining the nature of the acts and their potential consequences. For each scenario, a plant pathologist (J. Pinon for forest pathogens, I. Sache for cereal pathogens, and F. Suffert for the other pathogens) puts himself in the shoes of the perpetrator: he defined a tangible target (Table 2), selected the most appropriate pathogen from the list, and wrote a four to six pages essay (hereafter, scenario) describing the imagined agroterrorist act and its expected consequences. Considered as foresight tools for materializing the agroterrorist threat, the scenarios were kept confidential for evident security reasons. The three sections of the scenarios: "Synopsis" (*modus operandi* and expected consequences), "Justification" (geopolitical context and perpetrators' motivations), and "Feasibility" (perpetrators' ability to succeed and technical constraints) were substantiated with information extracted from relevant published and gray literature (i.e., body of materials that cannot be found easily through conventional systems of publication, bibliographic control, or acquisition by subscription agents). The nine key pathogens are *Tilletia indica* (the wheat Karnal bunt fungus), *Phytophthora infestans* (the potato late blight Oomycete) and *Pleospora papaveracea* (a potential opium poppy mycoherbicidal fungus) as

Table 2 A classification of agroterrorist acts and matching plant pathogens selected for the risk evaluation scheme (RES)

Type of scenario		Key pathogens[a]
Biowarfare		
BW1	Attack by a country on the agricultural sector of another country. The aim of the attacker is to block commercial imports of the targeted products and prevent their entry into its national market or to enhance its own exports.	*Tilletia indica* (*Ti*)
BW2	Attack by a country on the agricultural production of another country, in order to weaken the targeted country by reducing its domestic food supplies. This action could be undertaken before a military intervention or replace it.	*Phytophthora infestans* (*Pi*)
BW3	Use of biological agents by a country to eradicate illicit crops in another country (e.g., drug cultivation).	*Pleospora papaveracea* (*Pp*)
Bioterrorism		
BT1	Terrorist attack targeting food crops. The use of the agent may have negative impacts on human or animal health.	*Fusarium graminearum* (*Fg*)
BT2	Attack against crops or planted trees by ecowarriors who want to carry out a radical ecological action.	*Mycosphaerella populorum* (*Mp*)
BT3	Terrorist attack aimed at damaging a crop or a tree species that belongs to the national heritage.	*Ceratocystis fagacearum* (*Cf*)
Biocrime		
BC1	Attack by activists or farmers groups against the production of a competing country.	*Xylella fastidiosa* (*Xf*)
BC2	Isolated attack by an individual working in the crop protection field, looking for recognition, or revenge upon a colleague or an institution.	*Puccinia triticina* (*Pt*)
BC3	Deliberate use of a plant pathogen by a private company. The aim would be to render farmers dependant on specific cultivars or plant protection products.	*Phakopsora pachyrhizi* (*Pp*)

[a] Extracted from the list of 50 candidate plant pathogens delivered to the European Commission in the final report of the "CropBioterror" EU project

biowarfare agents, *Fusarium graminearum* (a grain-infecting, toxinogenic fungus), *Mycosphaerella populorum* (the poplar stem canker fungus) and *Ceratocystis fagacearum* (the oak wilt fungus) as bioterrorism agents, and *Xylella fastidiosa* (the grapevine Pierce's disease bacterium), *Puccinia triticina* (the wheat brown rust fungus) and *Phakopsora pachyrhizi* (the soybean rust fungus) as biocrime agents. The nine scenarios involving these nine pathogens were then ranked for specific features and salient components consistently highlighted in the literature on agroterrorism: diversity of impacts (on production, trade, society), interest for perpetrator to claim the attack, availability of technical means (origin of the scientific information and inoculum), possible contamination by aircraft (considered as a classical *modus operandi*), and potential countermeasures (early detection, control measures available).

The RES, which includes five sections (importance of the target crop, ease of use of the pathogen, epidemic potential of the pathogen, obstacles to swift and effective response to an attack, and potential global or regional consequences of an attack), was applied to the nine key pathogens selected for building the scenarios. Each section was scored on the [0–10] integer scale, using a series of qualitative and quantitative intermediate criteria as an aid to the overall assessment, detailed by Latxague et al. (2007). Each of the sections of the RES was plotted on a circumradius of a pentagon. The resulting pentagonal star plot was designed as a single multidimensional representation of the risk profile. While features and components of the scenarios were considered as non-exhaustive results (because they are selected examples, completed for only a given plant pathogen), the risk profiles, which quantify the risk associated to a given pathogen without specifying the perpetrators' objectives, were considered as exhaustive results (because they are completed taking into account each of the nine potential scenarios). The most important outcome, as usable and understandable by other risk assessors, the risk profile was summarized by an aggregated risk (R) computed for the stakeholders' sake. Such a score should be considered as a secondary product of the risk assessment rather than its main result. The aggregated risk (R) was calculated as the ratio of the area delimited by the variables' star to the total area of the pentagonal envelop of the plot as follows:

$$R = \frac{1}{n}\left(\left(\sum_{i=1}^{n=1} r_i \times r_{i+1}\right) + r_n \times r_1\right)$$

where r_i is the ith variable of the RES and n=5.

A critical feature of risk assessment is the evaluation the level of uncertainty encountered all along the assessment process. Communication of uncertainty contributes to transparency and may also be used for further identification of research priorities. In a PRA process, the panel of experts shall identify uncertainties related to the potential of entry, establishment and economic impact of a pest (EPPO 2007). In the present analysis, the risk assessor described the sources of uncertainty and the effects that the uncertainties may have on the risk assessment for each key pathogen. The main sources of uncertainty are missing, incomplete, inconsistent, or conflicting data (according to the scientific publications used) and controversial data or subjectiveness of analysis (according to the risk assessor). The degree of uncertainty (u) (scored on the [0–10] integer scale) was estimated in a final section of the RES.

Results

The 50 candidate pathogens include 35 fungi and oomycetes, nine bacteria and phytoplasmas and six viruses. Staple food crops represent the majority of the targets (24), followed by forest trees (11), industrial and market crops (ten), and orchard trees (five; Latxague et al. 2007). In 32 out of the 50 cases, direct crop loss is expected following an attack, while trade would be disrupted in 38 out of the 50 cases. Wider, indirect socio-economical consequences, such as poisoning of animals and humans, heritage and environmental loss or psychological negative effect on populations, are expected in 28 cases. The "top list" of the pathogens expected to cause together direct crop loss, trade disruption and indirect socio-economical consequences includes 14 pathogens. The list, however, does not claim to rank the pathogens according to the threat they represent for agriculture and forestry, since it does not consider either the feasibility of the malevolent act nor the reaction capacity after such an act. In addition, the list has been restricted to European crops, while agroterrorist attacks on non-European crops, such as rubber tree, coffee or cocoa, could also cause indirect but significant socio-economical damages to Europe.

The specific features and salient components of the nine analyzed scenarios are highlighted in Table 3. An act of agroterrorism requires a series of human choices based on the expected economical and psychological effects of the act, its technical feasibility and the reaction capacities, which would eventually decide the success of the attack. In contrast, the "success" of an accidental or weather-driven introduction of a quarantine pathogen mostly depends on the reaction (here, interception, early detection, eradication) capacities of the bodies in charge of plant protection. A mixed situation occurred in the few documented or suspected cases of deliberate introductions of a pathogen that failed because the pathogen escaped while expected to remain confined. For example, the emergence of tobacco

Table 3 Main features of nine examples of scenarios of agroterrorism (Table 2) scored using the qualitative scale: − low, + median, ++ high

Type of scenario (see Table 2)	BW1	BW2	BW3	BT1	BT2	BT3	BC1	BC2	BC3
Pathogen	*Ti*	*Pi*	*Pp*	*Fg*	*Mp*	*Cf*	*Xf*	*Pt*	*Pp*
Impact on:									
Production[a]	−	+	+	−	+	+	++	−	++
Trade[b]	++	−	−	−	+	+	−	−	−
Society[c]	−	+	−	++	+	++	+	−	+
Interest for perpetrator to claim the attack	−	−	−	+	+	+	−	−	−
Technical means									
Information on the Internet	−	−	−	+	++	+	−	−	−
Information from scientific publications (academic knowledge)	−	+	+	+	−	+	−	+	+
Strains collected from mycotheca	+	+	+	+	−	−	+	+	−
Contamination by aircraft	+	−	+	−	−	−	−	−	−
Probable countermeasures									
Early detection	+	−	+	+	+	−	+	−	+
Control measures available	+	+	−	+	−	+	+	+	−

[a] Yield losses

[b] Trade affected by phytosanitary measures such as import restrictions or embargoes

[c] Consequences on animal and human health, heritage and environment losses, or panic and psychological effects on civilian populations

blue mold in Europe, caused by the oomycete *Peronospora hyosciami* f.sp. *tabacina*, following its importation for research purpose in the United Kingdom and its unnoticed escape from greenhouses (Klinkowski 1961), can be used to explore or evaluate what happens in case of a successful agroterrorist attack. A key feature is the perpetrator's choice of the target crop and of the weapon pathogen, which will strongly depend on the expected effect of the attack. Instead of selecting the potentially most dangerous pathogens (the aforementioned "top list"), we have attempted to consider the perpetrator's point of view first. Table 3 shows that the nine scenarios represent a combination of different levels of direct crop loss, trade disruption and indirect socio-economical consequences. In these scenarios, the extreme situations are bioterrorism involving a quarantine pathogen targeting forests (BT3), with high potential level of direct crop loss, trade disruption and socio-economical consequences vs. biocrime involving individual revenge (BC2), with limited crop loss if any, no trade disruption and no significant socio-economical consequences (unless the epidemic runs out of control beyond the perpetrator's expectations). Pathogens with low effect on crop yield could be use for agroterrorism, provided they might disrupt trade via quarantine establishment (BW1) or produce toxins threatening human and animal health (BT1).

The main practical problem for the perpetrator is to gather the scientific and, mostly, technical information required for a successful act. For example, analyzing the black rust research program developed in the USA during the Cold War, Line and Griffith (2001) have pointed out that the dissemination of the pathogen was not the most critical problem and was not worth the effort made to set up innovative tools such as "feather bombs" or birds dusted with spores. Being able to increase and stockpile the inoculum in amounts required for a successful attack, which is usually not known, can be more difficult, as well as obtaining the inoculum from a public or private strain depository. Technical information on increase and storage of viable inoculum is, in most case, widely available on the Internet (with a reliability sometimes difficult to assess) and in scientific publications available in general or specialized libraries. Therefore, there are successive critical steps in the acquisition of knowledge; failure in attaining one of these steps would result in the abortion of the whole agroterrorist attack. In the state-sponsored biowarfare scenarios (BW) and corporate biocrime scenarios (BC3), there are no limitations of that kind. Other forms of malevolent acts, involving either individuals of terrorist groups, will require either the cooperation of scientists (scenario BC2 has a depraved scientist as the perpetrator) or the phishing of information in a roundabout way, and a certain level of laboratory and field skill. Agroterrorism has often been presented as easy (Rogers et al. 1999; Wheelis et al. 2002), but the scenario analysis led us to conclude that the success of a malevolent act might be much more uncertain than believed. Weather-driven or accidental introductions of quarantine plant-pathogens have such strong consequences on production and trade that is it often implicitly considered that the crisis result from a single, successful introduction, without considering the number of "attempts" required for a successful establishment of the pathogen.

The defeat of an agroterrorist attack seems to depend on the early detection of the pathogen and setup of countermeasures, as is the case for the eradication of quarantine pathogens (Schaad et al. 2003). Here again, this has to be modulated according to the perpetrators' expectations. A mass, state-sponsored biowarfare attack (BW1-3) should operate on a large scale, with several inoculation sites or an inundative approach in order to render ineffective the countermeasure system set up by the target country. Biocrime acts (BC1-3), operating on smaller scale, would be expected to avoid early detection and immediate eradication of the pathogen. Bioterrorist attacks (BT1-3) in contrast, should be "advertised" by the perpetrators in order to increase psychological confusion and disorganise the countermeasure system; such acts will probably target crops for which protection measures against the pathogen are difficult to implement or inefficient in order to even increase the perception of the threat.

The risk profiles set up for the nine selected pathogens are presented as pentagonal star plots, together with the risk aggregated scores, on Fig. 1. For example, the risk aggregated score R=36.0 assigned to *P. infestans* was calculated as $R=(r_1\times r_2+r_2\times r_3+r_3\times r_4+r_4\times r_5+r_5\times r_1)/5$, with r_1=8, r_2=6, r_3=6, r_4=4, and r_5=6). The highest aggregated risk score was assigned to *C. fagacearum* (R=60.4) while the lowest one was assigned to *P. papaveracea* (R=22.0). Regarding the individual components of the risk profile, r_1 (importance of the target crop) was maximal for wheat and maize and minimal for soybean and poppy (for Europe); r_2 (ease of use of the pathogen) was higher for the saprotrophic pathogens, in most cases easy to grow on artificial medium, than for the biotrophic pathogens, in most cases not cultivable on artificial medium; r_3 (epidemiological potential) was maximal for airborne pathogens already established in Europe and adapted to the local environment and minimal for soilborne pathogens and exotic pathogens expected not to adapt easily to the European weather conditions; r_4 (obstacles to swift and effective response to an attack) was maximal for pathogens unfamiliar to plant inspection services because they are either not present on the European territory yet or not accessible to quick detection methods (e.g., fungi attacking trees in mountainous, isolated areas); and r_5 (potential

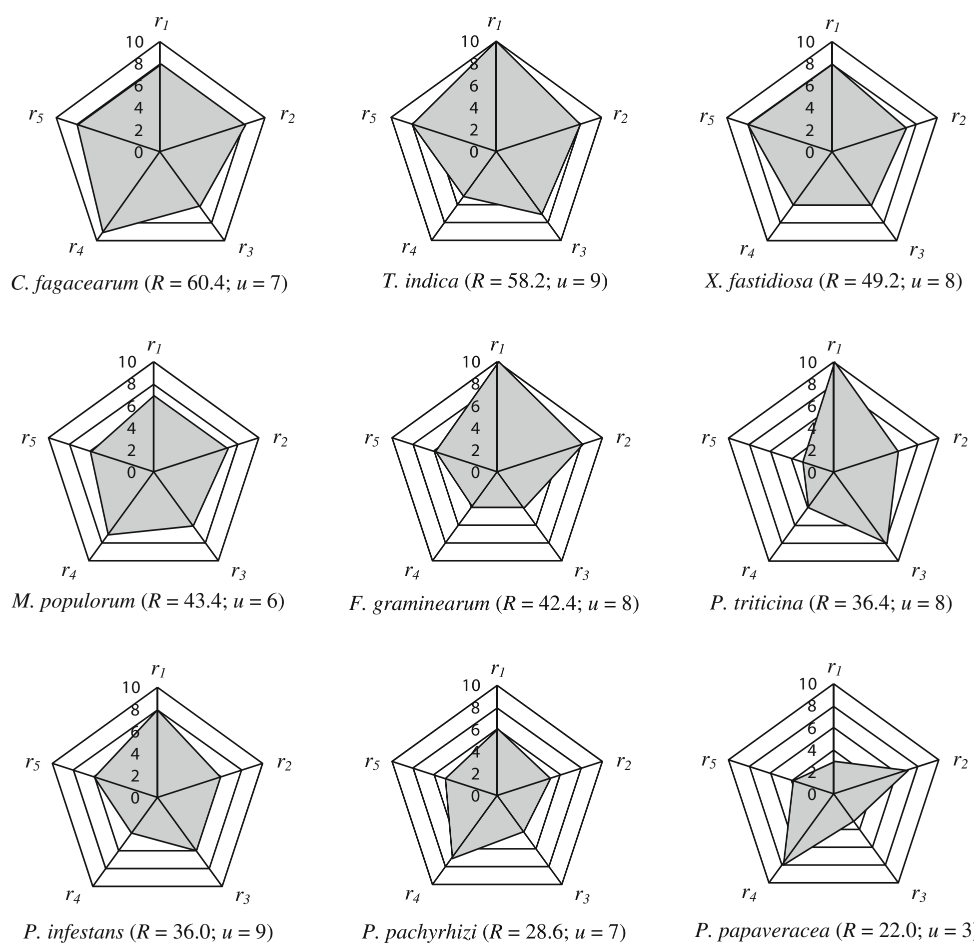

Fig. 1 Risk profile, completed by risk aggregated score and degree of uncertainty, as the result of the risk evaluation scheme (*RES*) for the nine selected plant pathogens. The five sections (scored on the [0–10] integer scale) of the RES are: importance of the target crop (r_1), ease of use of the pathogen (r_2), epidemic potential of the pathogen (r_3), obstacles to swift and effective response (r_4), potential global or regional consequences (r_5). The risk aggregated score R is given by the equation

$$R = \frac{1}{n}\left(\left(\sum_{i=1}^{n-1} r_i \times r_{i+1}\right) + r_n \times r_1\right)$$

with n=5. The degree of uncertainty u (scored on the [0–10] integer scale) is an empirical assessment of the quality and quantity of scientific information available for completing the RES global or regional consequences of an attack) was maximal for quarantine or regulated pathogens.

Discussion

Grown on large and often patchy areas, crops and forests cannot be entirely monitored and protected. Academic scientists and government stakeholders have started to reconsider the vulnerability of agro-ecosystems to plant pathogens used as anti-crop weapons because of the socio-economical significance of crops and forests (Rogers et al. 1999; Foxwell 2001; Madden and Wheelis 2003; Khetarpal and Gupta 2007). Crop biosecurity has become a subject of widespread concern, capitalized on the recent focus on emerging plant diseases (Anderson et al. 2004) and the world-wide, increasing interest in PRA for commodity trade regulation (Schrader and Unger 2003). Not specifically addressed until 1997 (Suffert et al. 2008), the agroterrorism issue was considered as even more critical in the USA after 2001. The 2002 US Agricultural Bioterrorism Protection Act had a worldwide impact on foreign operators that exported food or feed to the US: crop biosecurity has provided a new field for cooperation and standard practices at a regional scale, but agroterrorism prevention has also became an indirect potential obstacle to trade at the transnational level. Given this context, the constitution of a new bio-geopolitical order, of which agroterrorism is a component, is based on scientific discourses that incorporate economic and diplomatic components to phytosanitary measures and PRA schemes (Suffert et al. 2008); this parallels the incorporation of the specificities of the European agriculture between 1878 and 1929, into the international phytopathological conventions (Castonguay 2005). The lack of a consensual definition of agroterrorism, probably due to the recent interest in this topic, explains why the agroterrorist threat for European crops and forests was not exhaustively assessed by appropriate methods. Unverified allegations (Table 1) and alarmist papers (Rogers et al. 1999; Wheelis et al. 2002) did not favor the recognition of agroterrorism as the real threat which we believe it is. More controversially, we also believe that agroterrorism was sometimes treated as a buzzword in scientific literature since the beginning of the 2000s, and used by some crop protection scientists for the sake of fund-raising (Schwägerl 2005).

Risk assessment methods available in the literature, derived from population dynamic approaches (Madden and Van den Bosch 2002; Nutter 2004) are based on published epidemiological knowledge either on expert knowledge, regarding a specific crop (e.g., potato; Schaad et al. 2006), a pathogen group, or a research field (e.g., bacteriology; Young et al. 2008). Madden and Wheelis (2003) have designed a probabilistic method allowing, for a given plant pathogen, the computation of a global risk index. The index is the product of the probabilities of single events required for a successful agroterrorist attack (pathogen introduction, disease establishment, spread, damage and lack of control measures). Schaad et al. (2006) have applied a method based on an analytic hierarchy process to eight potato pathogens. Both approaches provide quantitative information (a global risk index), rather than qualitative information (a risk profile). In the probabilistic method, intermediate probabilities (*A*, probability that the pathogen will be deliberately introduced; *E*, probability of initial disease establishment; *S*, probability of spread from the initial established focus of disease; *H*, probability of the introduced disease causing major economic damage; *C*, probability of practically controlling or containing the disease) (Madden and Wheelis 2003) are assessed and multiplied to build the risk index. However, the product of probabilities, among whom some are probably extremely low (e.g., *A*), is not informative nor educational for risk assessment in general, because this does not show which components are high and which are low. The analytic hierarchy process is a general methodological approach for eliciting information from experts and is based on a set of prioritized and qualitatively assessed (high, mean, low) criteria (Schaad et al. 2006). While emphasis was put on the overall expected economic consequences of agroterrorist acts, the specific rating system did not consider the perpetrators' objectives, which precisely determine the nature of the threat. The proposed risk index did not explicitly enough take into account indirect economical consequences (trade disruption, scarcity), which are a specific feature of the agroterrorist issue (Turvey et al. 2003; Waage and Mumford 2007). In spite of the involvement of pathogens' experts, this method also appears much more as a theoretical exercise, of course very interesting, than a tool directly transferable to stakeholders, even if the rating system proposed by Schaad et al. (2006) was used once by banana growers (Ploetz 2008). In such approaches, the risk may be overestimated for a plant pathogen well-known to many experts in the assessment group.

The principle of transparency requires that every user of a risk assessment method can understand and reproduce the process, check the data used, adapt the method to specific situations, and re-evaluate previous outputs. Thus, the risk profile should be consistently substantiated and not purely based on expert judgment. Based on the scientific knowledge contained in ten scientific papers (if available), our method can be applied by non-experts on particular diseases or crops, thus authorizing a comparison between crops or pathogens with limited bias, on the basis on a complete threat characterization taking into account the perpetrators' objectives and expected consequences. Additionally, we should note that scientific information on a well-known pathogen will be probably more accessible to perpetrators, which may increase the risk, while the potential of early detection of the pathogen and setup of countermeasures will be higher, which may decrease the risk. The method generates a risk aggregated score together with a risk profile, which are necessary to understand the magnitude of the risk and to propose the most suitable countermeasures.

Because no anticrop agroterrorist act involving plant pathogens (excluding *de facto* human food poisoning) has ever been demonstrated, a prediction of the nature, the target crop, the pathogen introduced, and the perpetrator of "the most likely act" targeting crops is impossible. Our foresight approach was aimed at exploring the diversity of the potential scenarios, which are descriptions of possible, future issues. They consist of a list of conditions and assumptions, pertaining to potential attacks, and a list of rules. Used to derive the consequences of known and assumed future conditions, the rules are more or less formalized. Therefore the only subjective aspect of scenario studies is the choice of rules and conditions. While these particular choices can be questioned, the general validity of the deductive process is much less questionable. Previous assessment methods failed to consider the multiple facets of the risk represented by a given pathogen. Focused on regulated pathogens and relevant eradication measures, and on the direct crop loss, these methods did not explicitly take into account indirect economical consequences.

Forest and less anthropized (natural) ecosystems biosecurity deserves consideration as a full-fledged issue in a lot of countries (Cochrane and Haslett 2002). Mass destruction of food crops by the introduction of an exotic plant pathogen seems highly improbable in most advanced industrialised countries, where malevolent use of plant pathogens would more likely have a high social and economic impact. Some plant pathogenic fungi produce mycotoxins, which may potentially affect the human or cattle health. According to scenario BW1, these pathogens should be considered as a non-negligible threat for Europe, although most of them are already a recurrent cause of disease, such as *Fusarium graminearum* and *F. culmorum* on wheat, and *Penicilium expansum* on apples. Nevertheless, Russell and Paterson (2006) did not consider mycotoxin-producing fungi as serious anti-crop agents because of the low production of mycotoxins and the availability of detection methods. Based on biotechnical considerations, this opinion disregarded the potential psychological effects of a malevolent contamination of food on the population. A deliberate introduction of a plant pathogen may cause significant public panic and a loss of confidence in a segment or the whole of the food chain, seriously affecting niche sectors of European agriculture (e.g., organic farming). Additionally, a perpetrator with limited technical and scientific skills would increase the probability of success of his act by using simple intimidation or blackmail rather than attempting to contaminate his target: fear would have sufficient repercussions on trade and economy (Turvey et al. 2003; Waage and Mumford 2007).

When presenting here the results of a risk assessment of agroterrorism for Europe, we are aware that the consequences of assembling scientific knowledge and activities in this field of research need to be carefully considered, not only because research facilities are vulnerable to attack, but also because they could constitute entry points for perpetrators. While we may wonder whether the risk of agroterrorism has not increased over the last decade only because the problem has been raised, we disagree with Young et al. (2008) who appear to look at agroterrorism narrowly (causing "terror" *sensu stricto*). The capacity of European countries to prevent an act of agroterrorism requires the involvement of all parties interested in crop biosecurity, who are expected to consider the multiplicity of threats and to collaborate to implement countermeasures if required. This could include the support of the scientific community to additional regulations dealing with candidate pathogens. However we agree here with Young et al. (2008) that regulation in terms of national security may not be the most relevant approach to control pathogens fulfilling the proposed criteria for a biological weapon. Certainly failing to recognize the potential threat and being more concerned about maintaining complete freedom of research could result in major problems. In case of use of plant pathogen as anticrop weapon, an efficient response strategy would require to identify the source, the introduction method and time, and the perpetrators. Use of modern molecular-based detection technologies for early detection and identification of plant pathogens (Schaad et al. 2003) improves our ability to flag the emergence of "suspicious" epidemics (Waage and Mumford 2007; Suffert et al. 2008). We approve notably the establishment of a nationwide diagnostic network by the USA (Stack et al. 2006). Classic epidemiological methodology needs to be coupled with forensics, which is the application of scientific methods in the investigation of possible violations of the law, where scientific knowledge and technology provide evidence in both criminal and civil matters (Fletcher et al. 2006). Nevertheless, in two thirds of our scenarios, perpetrators would conceal their action, while claiming it would be efficient in one third of cases (Table 3). In this second case, a prevention strategy and countermeasures based exclusively on "early detection" would be inopportune and ineffective regards to the specific features of the scenario.

Every country member of the World Trade Organisation (WTO) has the right to impose import restrictions to protect the health of crops and forests, as long as no unfair discrimination or hidden trade barriers are created, and can decide which level of protection is appropriate for itself. Under the Sanitary and Phytosanitary Agreement (WTO 1995), import restrictions should be "technically" justified (i.e., "justified on the basis of conclusions reached by using an appropriate pest risk analysis or, where applicable, another comparable examination and evaluation of available scientific information"; IPPC 2004; Heather and Hallman 2008). Higher standards than those of the relevant international organisations are permissible only if justified "scientifically" according to an objective risk analysis. Precautionary measures lacking objective rationale should be allowed only temporarily, in emergency cases. In this context, we cannot exclude that a country, in bad faith, could consider that the probability of a "deliberate introduction" is temporarily high and that "agroterrorism" is a realistic pathogen entrance pathway, and use this threat as a technical justification to impose protectionist measures. It is also conceivable that a country clandestinely introduces a quarantine pathogen in a lot imported from another country to justify import restrictions and to protect its indigenous market. The global context of food crisis and the recurring difficulties in WTO negotiations caused by disagreement on rules governing agricultural trade make plausible the bio-geopolitical justification of some BW scenarios.

The community of plant pathologists seems to be divided, between, on the one hand, those considering the agroterrorist threat as doubtful (Young et al. 2008), and, on the other hand, those claiming that deliberate introduction of plant pathogens may constitute a threat serious enough to justify a scientific risk assessment (Madden and Wheelis 2003; Schaad et al. 2006; Suffert et al. 2008). The perception as to what a nation might consider an international threat, and what proper responses to it may be, is strongly influenced by cultural and political attitudes and by the historical perspective of that country (Suffert et al. 2008). Our opinion is that the level of risk is probably intermediate, but clearly more complex in its nature than perceived by some plant pathologists: agroterrorism is a real threat, potentially more important by the consequences of the securitization of the concept (Buzan et al. 1998; Waage and Mumford 2007), which could imply disruption of regulations and trade, as well as set up of new trade barriers, than by direct damaging consequences on crops. Whatever the opinion that scientists and stakeholders have about the "reality" of the threat, their reaction must be careful: risk assessment methods should be appropriate (transparent and reproducible) and scientific activity in Europe should not be inhibited by specific regulations (censure of scientific knowledge, restriction of exchanges of scientific material and scientists) (Pasquali 2006; Young et al. 2008).

Acknowledgments This work has been supported by the European Commission (6th PCRD grant, contract CT-2004-6403) in the framework of the EU project "CropBioterror". We thank Jean Pinon and Marc Barbier for their scientific contribution. The content of the present article only reflects the opinion of its authors, and not the opinions of either the European Commission or INRA.

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