



Addressing biohazards to food security in primary production

Annika Djurlé^{1,2} · Beth Young^{1,4} · Anna Berlin² · Ivar Vågsholm³ · Anne-Lie Blomström³ · Jim Nygren¹ · Anders Kvarnheden¹

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Abstract

This review addresses ways to prepare for and to mitigate effects of biohazards on primary production of crops and livestock. These biohazards can be natural or intentional introductions of pathogens, and they can cause major economic damage to farmers, the agricultural industry, society, and international trade. Agroterrorism is the intentional introduction of animal or plant pathogens into agricultural production systems with the intention to cause socioeconomic harm and generate public fear. Although few acts of agroterrorism are reported, the threat of agroterrorism in Europe is real. New concerns about threats arise from the rapid advancements in biotechnology and emerging technologies. FORSA, an analytical framework for risk and vulnerability analysis, was used to review how to prepare for and mitigate the possible effects of natural or intentional biohazards in agricultural production. Analyzing the effects of a biohazard event involves multiple scientific disciplines. A comprehensive analysis of biohazards therefore requires a systems approach. The preparedness and ability to manage events are strengthened by bolstered farm biosecurity, increased monitoring and laboratory capacity, improved inter-agency communication and resource allocation. The focus of this review is on Europe, but the insights gained have worldwide applications. The analytical framework used here is compared to other frameworks. With climate change, Covid-19 and the war in Ukraine, the supply chains are challenged, and we foresee increasing food prices associated with social tensions. Our food supply chain becomes more fragile with more unknowns, thereby increasing the needs for risk and vulnerability analyses, of which FORSA is one example.

Keywords Agricultural biohazards · Agroterrorism · Animal diseases · Food defence · Food security · Introduced pathogens · Plant diseases

1 Agriculture and food security

Agriculture plays a key role in maintaining welfare and social, economic, and political stability by providing essential food products. A secure food supply is one of the basic

tenets of modern societies and what many citizens expect from their government. Food supply and food security are constantly facing risks related to weather, lack of input resources, diseases, and national or international conflicts as well as threats by intentional and unintentional actions (Fig. 1). Agricultural commodities and their production, storage, and distribution could become targets for attacks that aim to disrupt socioeconomic stability. Disruptions to agriculture could be, for example, the introduction of pathogens (parasites, bacteria, viruses, and fungi) into crops and livestock herds potentially resulting in disease outbreaks, transmission of infections to other hosts, or infestations of seed or plant material.

1.1 What is agroterrorism?

The term agroterrorism is used to describe the intentional release of plant pests or animal pathogens with the goal

✉ Anders Kvarnheden
Anders.Kvarnheden@slu.se

¹ Department of Plant Biology, Swedish University of Agricultural Sciences, Uppsala, Sweden

² Department of Forest Mycology and Plant Pathology, Swedish University of Agricultural Sciences, Uppsala, Sweden

³ Department of Biomedical Sciences and Veterinary Public Health, Swedish University of Agricultural Sciences, Uppsala, Sweden

⁴ Department of Epidemiology and Disease Control, National Veterinary Institute, Uppsala, Sweden

Fig. 1 Matrix of different types of risks to food security and examples of actions. Modified after Spink and Moyer (2011)

Motivation	Gain Economic	Food quality Defective labelling Blown pack spoilage of vacuum-packed meat	Food fraud Illegal additives Incorrect labelling Beef substituted with horse meat
	Harm Public health, economic, warfare or terror	Food safety Salmonella EHEC contamination of unpasteurized milk	Food defence Toxins, pathogens or sharp objects added to food items
		Unintentional	Intentional
		Action	

to cause economic damage, undermine social stability and generate public fear. This could be done by a state, a group, or an individual in the form of biowarfare, bioterror or biocrime (Chalk, 2004; Foxell, 2001; Latxague et al., 2007; Mumford et al., 2017). In this review, agroterrorism refers to any attack using a biological agent against any on-farm agricultural commodity. Acts of agroterrorism may be difficult to distinguish from unintentional or natural introductions of pathogens, but all of them require the same preparedness planning and management, at least until the origin of an introduction has been confirmed. The resulting damage can be considerable regardless of whether the introduction is deliberate, accidental, or natural (Table 1).

In the past, the focus of biosecurity measures in European agriculture was on managing natural or accidental pathogen introductions (Suffert, 2017). However, over the past two decades, agroterrorism has gained increased attention (Green et al., 2017; Suffert, 2017; Mackelprang & Friedman, 2021). There are also increasing concerns that the continuing rapid advancements in biotechnology, and emergence of 4th industrial revolution technologies, could enable or facilitate the development of biological weapons and the creation of adapted harmful pathogens that could be used in agroterror attacks (Koblentz, 2020; Selgelid, 2009).

This review addresses ways to prepare for and mitigate possible effects of natural biohazards and agroterrorism on primary production of crops and livestock. The structure is based on an analytical framework called the FORSA model (Winehav & Nevhage, 2011). It was developed in Sweden as a tool in risk and vulnerability analysis of important societal activities and functions at local, regional, and governmental level. While the focus is on the situation in Europe, worldwide application of the approach presented here is possible. The usefulness of this and other approaches will be discussed.

2 FORSA—An analytical framework for risk and vulnerability analysis

A risk analysis consists of risk assessment, risk management, and risk communication (EU, 2002; FAO, 2007; IPPC, 2007). In risk assessment, risks are identified, analysed and evaluated in a systematic way and form the base for risk management. There are inconsistencies in the use of the terms risk analysis and risk assessment (cf. Anon, 2018; FAO, 2007), and here we follow the FAO outline (FAO, 2007).

Analytical frameworks for risk analysis are used to define the steps in the analysis and their relations (examples are discussed in Sect. 3). The FORSA framework was developed by the Swedish Defence Research Agency (FOI) (Winehav & Nevhage, 2011), and consists of six successive steps (Fig. 2). Here, we use the framework to organise the information required to address potential agroterror acts and other biohazards to primary crop and livestock production intended for human consumption. The steps include:

- I. Description of the function for society itself, including critical dependencies on other functions.
- II. Identification and characterization of unwanted or unexpected events, or threats, and their respective likelihoods.
- III. Description of the effects of an event on the function that was identified in the previous step. It includes the identification of vulnerabilities, methods, options and capabilities to manage risk, along with the resources this requires.
- IV. Actions to manage an acute event, eliminate or reduce threats and vulnerabilities, and strengthen the ability to manage a crisis.
- V. The methods and data used in steps I-IV.

Table 1 Historical examples of agroterrorism (biowarfare, bioterror, biocrime) and outbreaks after natural pathogen introductions in livestock and crops

Year	Location	Type of action, agent, sequence of events	Outcome and losses	Reference
WW I 1914–1918	US/Germany	Biowarfare: Draft horses infected with <i>Bacillus anthracis</i> and <i>Burkholderia mallei</i> by German agents before shipment to Europe	3 500 horses infected	Foxell, 2001
1952	Kenya	Bioterror: MauMau used plant toxin to kill British-owned livestock	Thirty-three animals poisoned, of which 8 died	Carus, 1998
1985	Mexico – US border	Biocrime: Workers spread screwworm (<i>Cochliomyia hominivorax</i>) among livestock in the area to protect jobs	Unknown fatalities and injuries	Mohtadi & Murshid, 2006; Keremidis et al., 2013
1997	New Zealand	Biocrime: Farmers deliberately introduced Rabbit hemorrhagic disease virus (RHDV) into country	Virus became established in the wild rabbit population	Wilson et al., 2000; O'Hara, 2006
2005	New Zealand	Agroterrorism hoax: False claim of deliberate release of Foot and mouth disease virus (FMDV)	NZD 1.5 and 2 million	Mackereth & Stone, 2006; Farsang et al., 2013
Late 1980s	Uganda	Natural outbreak: Indigenous Cassava mosaic disease (CMD) virus adapts to introduced crop	Spread to 10 other countries in East and Central Africa.	Jones, 2020
1997	USA	Natural outbreak: Karnal bunt in wheat caused by <i>Tilletia indica</i>	Devastating yield loss, loss of income, food shortage, famine, and deaths	Cupp et al., 2004
2001	United Kingdom	Natural outbreak: Foot and mouth disease (FMD)	Trade restriction from 50 countries USD 250 million reduction in wheat exports 6 million animals slaughtered GBP 3.1 billion lost for agriculture, food industry and public sector (EUR 3.4) and GBP > 5 billion in lost revenues for tourism and other supporting industries	NAO, 2002; Thompson et al., 2002
Early 2000s	Western Europe (several countries)	Natural outbreak: Mad cow disease (BSE) in cattle	Import bans of beef from EU to Russia and Egypt	Fox & Peterson, 2002
2006–2018	Germany	Natural outbreak: Bluetongue (BT) in cattle and sheep	> 60 000 infections and 17 000 deaths EUR 48 million direct loss, EUR 132 million indirect loss	Conraths et al., 2009; Gethmann et al., 2020

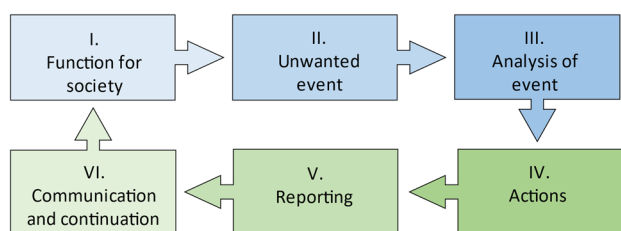


Fig. 2 The FORSA framework. After Winehav and Nevhage (2011), modified

- VI. The decisions that are made on the ways to convey the results to stakeholders and to ensure that risk management actions are implemented.

This framework can be used to address both natural and intentional biohazards, and in the following sub-sections, actions in each step of the framework are described.

2.1 Step I—Function for society

The first step in the risk and vulnerability analysis describes the function for society (Fig. 2), which in this case is primary crop and livestock production for food, that may lead to diseases or other direct damage to livestock or crops. Threats, risks, vulnerabilities, and critical dependencies are identified along with the resources that are available to reduce serious disturbances.

2.1.1 Farming in Europe

The contribution of agriculture to maintaining private and public activity is significant and important for rural employment and development (Table 2). Agriculture also generates raw materials for businesses and secondary industries, employing millions of people. The food industry is the largest manufacturing industry in the EU (Food-DrinkEurope, 2020). Thus, any unexpected disruption event in the primary production would not only directly affect farmers, but it would also have indirect effects on the secondary industries, as well as on international trade.

Over the last century, farming in Europe has changed dramatically, including a trend towards fewer and larger, farming operations (Eurostat, 2018). In the past, agriculture was a highly localized industry where crops and animals were raised, harvested, and processed on-farm or within the same region. Today's farms are more specialized and focus on the production of few commodities (European Commission, 2013; Abson, 2019). Many goods and services, which were previously provided locally, are now provided by outside contractors and private companies. This has resulted in a shift to agricultural production where animals, grains, agricultural supplies, and food products are unevenly distributed throughout the world and transported over large distances (Greger, 2007; Niemi, 2012). The EU's Common Agricultural Policy (CAP) regulates production, prices, and markets (European Commission, 2018a).

2.1.2 Changing attitudes towards agriculture

The number of people living in rural areas has been decreasing since the 1950s (World Bank, 2019), so for many people, the connection between agriculture and food production has been lost. The result is a public that has a sense of security generated by a plentiful supply of safe and healthy food in stores, but with a limited appreciation for agriculture's role in society. The limited contact that people have with agriculture also means that fewer persons pursue careers within the agro-industry, food animal medicine or plant pathology (Dunning et al., 2009; Gullino, 2009; Kelly, 2005; MacDonald et al., 2009). If this leads to job vacancies, it could add to a country's vulnerability to biohazards and agroterrorism. A lack of veterinarians or agriculture experts could delay the diagnosis of an emerging disease or the identification of an antagonistic release of a pathogen, allowing the disease to spread more widely.

2.1.3 Farm security and biosecurity

Many farms operate in an open manner with few physical security measures to prevent unauthorized access, especially to outlying fields and pastures (Crutchley et al.,

Table 2 Contribution and economic importance of food production to welfare (World Bank, 2021)

	World	European Union	East Asia & Pacific / South Asia*	Sub-Saharan Africa*
Agricultural land, million sq.km (2016)	48.6	1.6	7.8 / 2.7	10.2
Agricultural land, % of total (2016)	37.4	41.1	48.8 / 56.8	43.7
Contribution to GDP—Agriculture, fisheries and forestry (2019), %	3.3	1.6	7.8 / 16.3	14.1
Employment in agriculture of total (2020), %	26.5	4.2	26.8 / 40.8	52.4
Rural population of total population % (2019)	44.3	25.3	65.5 / 43.4	59.3

*Excluding high-income countries

2007). Farm biosecurity refers to the measures to protect a farm against introduction of pathogens and to minimize their spread within a farm and beyond (CFIA, 2013). Farm biosecurity is important to consider when looking at vulnerability to agroterrorist attacks, particularly in intensive production systems. In recent years, few European countries have suffered major losses due to agricultural disease outbreaks, which can lull people into the false sense that their production systems are safe and protected (Chalk, 2004; Crutchley et al., 2007). These attitudes could be changed by increased knowledge about the benefits of implementing higher biosecurity levels compared to their costs (Kristensen & Jakobsen, 2011; Laanen et al., 2014). A high level of farm biosecurity, including new technologies, would limit potential introduction of a biological agent into a crop or group of animals (Jurdak et al., 2015; Hu et al., 2020; Kakani et al., 2020; Koblenz, 2020).

2.1.4 Legal frameworks

All EU members are required to have a national capacity to perform pest and disease risk assessments (PRA), as stated in the Animal Health Law and The Plant Health Law, and in the International Plant Protection Convention (IPPC) (EU, 2016a, b; IPPC, 1997). The PRA are the base for the development of risk management plans. These regulations apply regardless of whether outbreaks are intentional or not.

Regulations and lists of pathogens are established with the aims to build awareness of potential risks and to prevent pathogen introductions and disease outbreaks (Table 3). Since many of the agents on these lists lack the desired characteristics of an agroterrorism agent (See Annex 1), additional lists of high-threat agricultural pathogens have been compiled (Wilson et al., 2000; Madden & Wheelis, 2003; Schaad et al., 2006; Suffert et al., 2009; Kamenidou et al., 2013; Suffert, 2017). It is impossible to produce a common short list of high-threat pathogens because the threat level varies depending on, for example, location, perpetrators, motives, and the intended target (Madden & Wheelis, 2003; Suffert et al., 2009). Sometimes biological information about pathogens is lacking, in which case list developers rely on expert opinion and educated guesses (Schaad et al., 2006). Despite these problems, creating lists of potential threat agents is an important aspect of preparedness to counter agroterrorism (Madden & Wheelis, 2003).

2.2 Step II—Unwanted event

The second step of a risk and vulnerability analysis, includes identification of specific unwanted events, and evaluation of their risks, vulnerabilities, and critical dependencies. The

Table 3 International lists of major threats among animal and plant pathogens and diseases

Name of list	List creator	Aim	Content	References
OIE list of notifiable terrestrial and aquatic animal diseases	World Organisation for Animal Health (OIE), 181 member states	Inform on notifiable animal diseases	Listed pathogens are of serious socio-economic or public health importance. Pathogens considered as the greatest agroterror threat to livestock	Wheelis et al., 2002; Chalk, 2004; Ungerer & Rogers, 2006; OIE, 2021
EPPO A1/A2 lists of pests recommended for regulation as quarantine pests	European Plant Protection Organization (EPPO), 52 member states	Prevent natural or accidental introductions in connection with international trade	Pathogens recommended for regulation as quarantine pests by the member countries	Suffert, 2017; EPPO, 2020; European Commission, 2020a
EU Regulation 2019/2072	European Commission, 27 member states	Prevent natural or accidental introductions in connection with international trade	Quarantine pests and Regulated non-quarantine pests. Relies on EPPO's recommendations	Suffert, 2017; European Commission, 2020a
Australia group common control lists	Australia group (AG), informal group of 43 states incl. EU	Ensure exports do not contribute to biological weapons proliferation	Lists of animal and plant pathogens deemed to be at risk of being used as biological weapons	Australia Group, 2007

likelihood of an event, for example the intentional introduction of an animal or plant pathogen, and its consequences and uncertainties, is quantified. Risk matrices are useful to illustrate the relationships between likelihoods and consequences, based on current knowledge and assessments, especially when quantitative data is scarce or uncertain (Van der Fels-Klerx et al., 2018) (Fig. 3).

2.2.1 Pathogens and diseases of concern

Natural disease outbreaks can be predicted to some extent, and they have similarities with previous outbreaks (Treadwell et al., 2003). This knowledge is used in conventional disease risk analyses, which are the base for disease response plans. Annex 2 gives examples of pathogens that constitute serious threats to food security. In case of an intentional pathogen release, the predictabilities of an outbreak are replaced by uncertainties through the calculated actions of the perpetrator who can select the agent, target, location, and the scale and timing of the release (Mumford et al., 2017; Treadwell et al., 2003). For example, a pathogen could be released in several geographically distant locations to initiate multiple, simultaneous outbreaks (Elbers & Knutsson, 2013; Mackelprang & Friedman, 2021). Manipulations that bypass conventional biosecurity measures and exploit existing vulnerabilities may thus cause an outbreak that plays out differently from a natural outbreak. This could overwhelm a nation's response capacity, leading to the uncontrolled dispersal of a pathogen and spread of the disease (Elbers & Knutsson, 2013).

Very few plant pathogens pose a risk to human health. However, some fungi, such as the cereal pathogens *Fusarium* spp., which causes fusarium head blight and ear rot, and *Claviceps purpurea*, which causes ergot, produce mycotoxins that can result in acute and chronic disease or death in humans and animals. The risk of mycotoxins entering the food chain is low due to good detection methods, and regular

testing of harvested grains, food, and feed for mycotoxin contamination (Alshannaq & Yu, 2017; Paterson, 2006). On the other hand, use of mycotoxin-producing fungi as an agroterror weapon can potentially have human and animal health effects and result in economic damage as infested grains can become unfit for consumption.

Many livestock diseases, such as Rift Valley Fever, Congo Crimean Haemorrhagic Fever and Avian Influenza, are zoonotic which means that they can be transmitted between animals and humans. However, human-to-human transmission of these diseases is rare. Therefore, an agroterror attack using a zoonotic pathogen is unlikely to cause a widespread outbreak among people, but farm workers, veterinarians, and persons having direct contact with infected animals face the risk of becoming ill (Hueston & Singleton, 2010).

2.2.2 Dilemmas with synthetic biology

Recent discoveries and developments in molecular genetics and synthetic biology have allowed for precise changes in the genome of living organisms. These advances have led to research that increases our understanding of how pathogens infect hosts which has aided in development of more effective vaccines and increased the speed at which vaccines can be manufactured in response to disease outbreaks (DiEuliis et al., 2017). However, with the advent of increasingly sophisticated methods for altering organisms at the molecular level, there are concerns about the potential to use artificially created or genetically altered biological agents as weapons (Drew & Mueller-Dobies, 2017). The need to balance the advancement of beneficial life sciences research with the need to prevent further development of biological weapons is known as the 'dual-use dilemma' (Atlas & Dando, 2006; Selgelid, 2009), and research that is intended for benefit, but which also could be applied to cause harm, is referred to as 'dual-use research of concern' (DURC) (Imperiale & Casadevall, 2015).

Openly sharing information is vital for the scientific community, but it also provides would-be proliferators of biological weapons easy access to new knowledge and techniques (Anand, 2018). There are numerous scientific papers describing research that is considered as DURC (WHO, 2010; Valles & Bernacchi, 2014), and several examples of how it can be addressed scientifically and ethically (Atlas & Dando, 2006; Selgelid, 2009; Imperiale & Casadevall, 2015; Selgelid, 2016; Drew & Mueller-Dobies, 2017; Anand, 2018; Imperiale & Casadevall, 2020). In addition, the risks for malicious use of new techniques and emerging technologies such as the use of drones, digital equipment, and 3D-printing requires preventive actions from policymakers (Bajema, 2018; Koblenz, 2020).

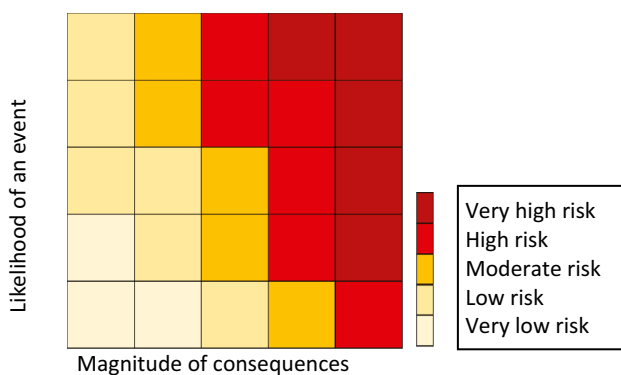


Fig. 3 A typical risk matrix showing results from a risk analysis

2.2.3 Dispersal and long-distance movement of pathogens

The natural processes of pathogen dispersal, especially by wind and vectors, may be difficult to control. In addition, human activities may also contribute to pathogen dispersal. Long-distance movements of agricultural commodities increase the possibilities for pathogen dispersal beyond the original site of introduction (Crutchley et al., 2007; Dunn, 1999; Wu et al., 2021). For animals, the stress of prolonged transport can have an immunosuppressive effect and increase their susceptibility to disease (Greger, 2007). A study tracking the movements of Swedish livestock hauliers showed that vast areas are covered in short periods of time (Olofsson et al., 2014). A highly contagious pathogen could then easily be dispersed over a very large area before animals show disease symptoms (Olofsson et al., 2014). When examining long-distance movements, the vehicles, boots, clothing, and other equipment that can transmit pathogens between fields and farm sites need attention, in addition to the commodities themselves.

2.2.4 Identification of vulnerabilities

A deliberately introduced pathogen can disperse quickly through animal or plant populations in a country or region. Usually, agricultural animals are not naturally exposed to many infectious diseases and will be neither immune nor vaccinated against these diseases. The resulting lack of herd immunity increases their vulnerability to deliberate attacks (Ungerer & Rogers, 2006), as would limited stocks of vaccines. Similarly, certain plant pathogens and pests are currently not found in Europe, and little attention is paid to integrating resistance to them in the varieties grown. In case of an introduction these crops will be susceptible. Although several plant pathogens may be managed by pesticides, their availability depends on whether a product is approved in a country (EU, 2009; European Chemicals Agency, 2021), if it is approved to be used in the crop at risk, and if the quantity in stock covers the need in an outbreak situation.

Vulnerability to disease outbreaks increases with large or dense populations of susceptible plants or animals. The trend toward increased farm size, homogenous crop distribution, and regional concentration of production often results in large populations of susceptible hosts in small areas (Dorea et al., 2017; Foxell, 2001; Gilligan, 2008; McDonald & Stukenbrock, 2016; Meadows et al., 2018). Widespread use of crop varieties with a narrow genetic base increases vulnerability to new pathogens or new variants of known pathogens (McDonald & Stukenbrock, 2016; Zhan et al., 2015). The vulnerability of crops to all types of biohazards also increases if there is too much reliance on previous success in managing a disease. For example, while the viruses causing

virus yellows of sugar beet were managed with neonicotinoids, the development of alternative management methods, such as virus-resistant cultivars, was neglected. After the use of neonicotinoids in the EU was banned, virus yellows has re-emerged as an immediate threat to sugar beet cultivation (Hossain et al., 2021).

The ability to quickly identify the pathogen is crucial for early and appropriate control measures in the event of a deliberate or unintentional introduction. It can become extremely costly if the identification of a pathogen is delayed or fails due to a lack of training (Dorea et al., 2017; Hammond et al., 2016; Wright et al., 2016). Veterinarians, plant pathologists, and other agricultural experts often have limited experience in identification and management of exotic diseases because they are seldom found (Elbers & Knutsson, 2013; Thelau et al., 2017). Adequate monitoring and surveillance systems are needed so that a pathogen does not go undetected, and disease outbreaks are managed in time.

2.3 Step III—Analysis of event

The third step in the analysis describes possible consequences of an unwanted event affecting the function for society, the abilities to mitigate them, and the resources that are available or needed. Vulnerabilities and critical dependencies are rated on scales that express the seriousness of the consequences, and the abilities to mitigate or manage an event. These scales are often qualitative descriptions based on current knowledge, experience from other events, and expert judgements or knowledge elicitations. For evaluation and comparison of risk scenarios, the qualitative scales can be made quantitative or semi-quantitative by ranking e.g., likelihoods, impacts, or frequencies in time intervals on nominal (e.g., good to poor) or ordinal scales (e.g., 1–5) (Léger et al., 2017; Robb, 2017; EFSA PLH Panel et al., 2018; Van der Fels-Klerx et al., 2018). Another way is to create scores based on exposure, sensitivity and adaptive capacity (Fontaine & Steinemann, 2009). Descriptions of consequences in categories such as the specific effects on health, environment, economy, and extent and duration of the event would be informative. However, to be useful they must be established in advance, and collaboratively between all actors (Utne et al., 2008). The consequences of a crisis become difficult to handle when it is uncertain what the hazards will be (Frykmer et al., 2018; Utne et al., 2008).

The mitigation and management of an unintentional or deliberate introduction of a disease requires a systematic and systems-oriented approach, even if the introduction is limited (Anand, 2018). In this step, further analysis of the consequences is possible, and the risk matrix from step II can be updated with new facts (Fig. 3). The continued analysis will be based on the estimates of consequences in this step.

2.3.1 Economic effects

Animal and plant diseases can cause considerable losses (FAO, 2016; Oerke, 2006; Savary et al., 2019). Even limited outbreaks of diseases, most of them natural, have resulted in substantial economic losses (Table 1). The losses incurred during agroterrorism attacks would be similar since the measures taken to control a disease outbreak are the same regardless of its cause (Hugh-Jones & Brown, 2006).

An agroterror attack or other biohazard in primary crop or livestock production will result in quantitative and qualitative losses for the farmer(s) involved. In addition to these losses, a biohazard event will have socio-economic consequences on three levels: direct, indirect, and for international trade (Chalk, 2004). The measures to manage the indirect losses vary depending on the introduced pathogen, and they can be costly, even if the affected commodity's contribution to the economy is small. However, in the long-term, the gains from appropriate management should outweigh the costs (Wheelis et al., 2002). The losses from a disease outbreak to secondary industries and the society's economy are expected to be similar to those of the affected primary industry, or larger (Blake et al., 2003; Petterson & Widell, 2010).

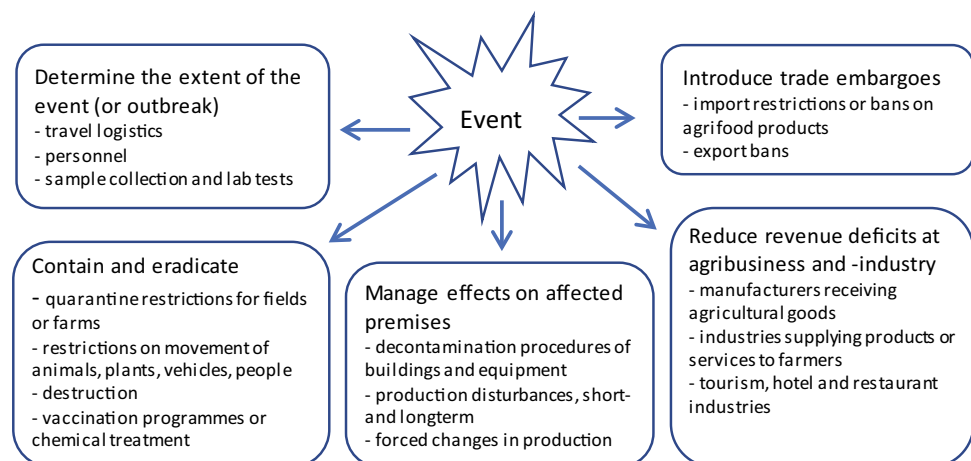
The direct and indirect economic losses, other than those experienced by the farmer, are seldom presented and, if so, mostly in qualitative terms. It is particularly hard to derive the estimates of indirect losses. Sampling routines and intensities are not designed to estimate loss to society (Madden et al., 2007), and losses to other actors in the food production chain are more difficult to disentangle (Yudelma et al., 1998). The process to identify abilities and resources that are needed for the mitigation of an unwanted event and to foresee vulnerabilities would be strengthened with advancements in the identification and quantification of the direct and indirect losses (Madden & Wheelis, 2003; Chalk, 2004; Suffert et al., 2009; Gamliel & Fletcher, 2017a) (Fig. 4).

International trade losses arise when trade embargoes are imposed by a country's trading partners (Chalk, 2004). Every member of the World Trade Organization (WTO) has the right to impose import restrictions to protect public, animal, and plant health, and decide on an appropriate level of protection (Suffert et al., 2009). The detection of a disease in one country can result in import restrictions or bans on agri-food products by other countries. Such bans can take months or years to resolve and trade volumes may never return to those existing prior to the outbreak (Hueston & Singleton, 2010). The severity of trade implications due to an animal or plant disease outbreak depends on the size of the export markets for the affected country (Kahn, 2019; Keygene, 2019; Tozer & Marsh, 2012).

When public confidence in food security is undermined, it has a significant impact on consumer trust and demand (Evans, 2006), and results in reduced consumption of the affected products, even if there is no real cause for concern to human health (Clarke & Rinderknecht, 2011). For example, domestic chicken consumption dropped by up to 30% in some European and Asian countries after outbreaks of Avian Influenza (Kraipornsak, 2010; Valceschini, 2006). Spanish cucumber growers were severely affected when consumption and export of their cucumbers halted after they were wrongly suspected of being the source of an *Escherichia coli* outbreak in Germany in 2011, which was ultimately traced to contaminated fenugreek seeds (*Trigonella foenum-graecum*) for sprouts from Egypt (Burger, 2012). Consumer demand for the affected foodstuff could be reduced to a greater extent if a food safety scare resulted from agroterrorism than if it were due to a natural disease outbreak (Just et al., 2009; Turvey et al., 2010).

Food prices would increase if an accidental or deliberate introduction of a disease or pest results in a food supply shortage (Linacre et al., 2005; McDonald, 2013). In medium- or low-income countries this could cause consumer discontent, and political instability (Arezki & Brückner, 2011). To

Fig. 4 Abilities and functions required to reduce damage from an unexpected event



what degree increased imports could compensate for a shortage would depend on trade arrangements, with food security being higher in countries with an openness to trade (Dithmer & Abdulai, 2017). The most vulnerable countries would be low-income countries and countries with a high proportion of GDP coming from agriculture, economic dependence on cash crops, insufficient self-sufficiency for basic food items, undersized border control, low farm biosecurity combined with intensive farming, and few resources for extension systems and monitoring (Anand, 2018; Dithmer & Abdulai, 2017; Linacre et al., 2005; Sundström et al., 2014).

2.3.2 Political, health-related, and social effects

In addition to the economic impact of a biohazard, there will be political, health-related, and social effects. A terrorist attack on agriculture could change the political climate in a country. It is likely to affect the public's trust in their government's preparedness to manage biohazards and the ability to provide adequate quality control of their food supply, resulting in a decrease in consumer confidence in the safety of their food (Wilson et al., 2000; Cupp et al., 2004; Evans, 2006; Crutchley et al., 2007; Chalk, 2010; Hueston & Singleton, 2010).

After an agroterror attack, the physical health risks to the public are likely to be smaller than the mental health effects (Hueston & Singleton, 2010). A terrorist act resulting in a disease outbreak would be a highly distressing experience for those directly impacted by the event (Peck et al., 2005; Hueston & Singleton, 2010). Many people lack knowledge about how pathogens cause disease, so there is likely to be widespread anxiety and fear around attacks with pathogens (Crutchley et al., 2007). The health effects are likely to strain public health care systems, particularly in rural areas (Evans, 2006).

If the goal of terrorism is to weaken society by creating fear and feelings of vulnerability, the social effects on farmers, the extended agricultural sectors, communities and first responders dealing with the outcome of an attack should be recognized (Evans, 2006). Following the UK FMD outbreak, producers and communities were socially isolated due to closure of roads and schools, cancellation of events, and limited access to community support networks. Consequently, tension and long-lasting conflicts were seen in rural communities (Royal Society of Edinburgh, 2002; Becker, 2010).

2.4 Step IV—Actions

The fourth step in the risk and vulnerability analysis addresses actions to manage an acute and unexpected event, eliminate or reduce threats and vulnerabilities, and strengthen the ability to manage a crisis. The estimates of risks and consequences in the previous steps help to

identify necessary and possible actions, and their order of priority. The goal of all actions is to reduce the likelihood of an event, its consequences, or both (Fig. 3). At the farm level, the actions would address farm biosecurity. At the national level they would include surveillance and diagnosis, and at national and international levels, regulations and risk assessments. All actions will be considered from both economic and political angles since it is difficult to estimate the costs of the consequences (Utne et al., 2008). The key to successful short- and long-term management of a disease outbreak or an agroterror attack would be a joint and multisectoral response.

2.4.1 Farm biosecurity

Farms with a high level of biosecurity are more difficult targets and, in case of an event, the pathogen spread between farms may be slowed. An important step would be to increase farmers' knowledge and understanding of disease risks, and how responsibilities are shared between farmers and authorities (Higgins et al., 2016; Renault et al., 2020). If several channels and means for information distribution are used, the chances of reaching most farmers are increased (Nöremark & Sternberg-Lewerin, 2014).

According to EU regulations, all member states must establish national control plans (EU, 2016a). A biosecurity program for farmers includes training in prevention of disease spread, assessment of farms by a veterinarian with training in biosecurity and giving advice to farmers on how to improve their farm biosecurity.

2.4.2 Pest and disease risk assessment (PRA)

An important step in preparedness and response planning for agroterrorism is to determine which pathogens, out of hundreds, that pose the greatest threat, since it is not feasible to develop prevention and response plans for all (Fletcher et al., 2017; Schaad et al., 2006). A country's preparedness level would increase by adding and updating lists of high threat agroterror agents to their agricultural security policies and standards. The lists of high-threat pathogens would be useful as guidance for*:

- development of counter-terrorism strategies to prevent and deter the use of specific pathogens as weapons,
- research into more rapid and sensitive methods of detection and diagnosis of target diseases,
- risk assessments and epidemiological studies of disease spread,
- development of forensic biology methods that could help differentiate between deliberate and natural introductions

*(Madden & Wheelis, 2003)

Disease and pest risk assessments require regular revisions by individual nations in order to adhere to the Animal Health and the Plant Health Laws, respectively (EU, 2016a, b). Some advocate that disease and pest risk assessments should include agroterrorism-related factors, such as perpetrator motives and capability, and target vulnerabilities, since an agroterrorist attack may have a course that deviates from what is expected or known from naturally occurring disease outbreaks (Mumford et al., 2017; Suffert, 2017).

2.4.3 Surveillance and diagnosis

In recent years, counterterrorism efforts have become a political and national security priority. Unlike other acts of terrorism such as bombings and hijackings, which are carried out overtly, an act of agroterrorism is most likely to be a covert operation (Farsang et al., 2013). If the act is clandestine and because most biological agents are invisible, an attack may remain undetected until signs or symptoms of disease appear in exposed plants or animals at the end of the incubation period (several days to weeks), or until the detection threshold in affected plants or animals is reached (Madden & Wheelis, 2003; Zadoks & Schein, 1979). This makes early detection of an agroterror attack challenging (Farsang et al., 2013). In light of ongoing climate changes, unexpected disease outbreaks and introductions of pathogens are foreseeable, and their detection will require similar attentiveness.

In the EU, there are monitoring and surveillance programs for animal diseases, and plant pests and diseases (European Commission, 2008; EFSA et al., 2020b). An animal disease notification system (ADNS) is established, and quarantine priority plant pests are identified based on their potential for social, economic, and environmental damage (European Commission, 2012; EU, 2019). In addition, most countries have their own monitoring programs that provide evidence that certain pathogens and pests are absent from the country, and baseline prevalence information, and serve to detect the introduction of pathogens so that actions can be taken to prevent further spread (Elbers & Knutsson, 2013). Preparedness for plant disease outbreaks would be strengthened by a global disease surveillance system (Carvajal-Yepes et al., 2019). For economic reasons, active surveillance programs are not possible for all animal diseases or quarantine plant pests. Combined statistical and epidemiological models can be used when designing surveillance systems based on pathogen characteristics (Parnell et al., 2017), but no program is completely reliable.

Successful surveillance for high-threat pathogens depends on farmers, veterinarians, and plant protection specialists, and notifications of new disease outbreaks to the authorities are essential early detection tools (Elbers et al., 2010). Early detection therefore hinges on the ability to recognize

the signs and symptoms of unexpected diseases. If a disease has not been seen for many years, the signs may not be recognized, and may instead be assumed to be signs of endemic disease (Elbers et al., 2010). It is of utmost importance that those who work on the front lines of agricultural health, have education in disease recognition to ensure rapid detection (Elbers & Knutsson, 2013; Mackelprang & Friedman, 2021).

It is mandatory to report suspected high-threat pathogen infections to responsible authorities before any action can be taken. The reporting of suspect disease cases should be uncomplicated and could be encouraged by financial compensation, or fines upon un-reported outbreaks. If producers must pay for a pest eradication, they will be encouraged to adopt preventive measures (Centner & Ferreira, 2012; Wilkinson et al., 2011).

Early detection and identification of a pathogen minimizes delay and the costs of management actions and increases the likelihood of success (Karlsson et al., 2013). EU regulations require that Member States have sufficient capacity for diagnosis of animal and plant pathogens and pests (EU, 2016a, b). In addition, there are requirements for having National Reference Laboratories and designated EU Community Reference Laboratories for diagnosing animal and plant pathogens and pests (EU, 2017; European Commission, 2018b). At these laboratories, it should be possible to identify most pathogens that could be used in an agroterror attack or introduced by neglect of the regulations. In the United States, the National plant disease diagnostic network (NPDN) is a valuable platform for information exchange, collaboration between diagnostic laboratories, and other activities that strengthen national biosecurity (Stack et al., 2014).

In addition to the identification of pathogens and diseases, there are methods for determining if a disease outbreak is of natural or malicious origin, and whether an organism was genetically modified or not (Elworth et al., 2020; Lewis et al., 2020; Pilch et al., 2020). Unless a perpetrator's goal is to claim responsibility for an action, technologies that can attribute perpetrators to malicious actions, may have a deterrent effect, and lead to conviction of crime or diplomatic penalties (Lewis et al., 2020).

During a crisis event, the capacity of individual laboratories could quickly be exceeded by the large number of samples to be analysed. To address this problem, laboratory networks that strengthen capacity and capabilities through, for example, sharing sample analysis duties can be formed. This was useful in Sweden during naturally occurring outbreaks of anthrax in 2008 and 2011 and during the Covid-19 pandemic in 2020–2021 (Lindberg & Melin, 2016; SVA, 2021). Other important areas for enhancing bio-preparedness in national laboratories include ring trials, maintaining competence, sample transport and delivery, inter-agency communication and sharing of data (Thelaus et al., 2017).

2.4.4 Response to unwanted events

An efficient response to an agroterror attack or unintentional introduction requires a multidisciplinary and multisectoral approach that includes private and government health services, law enforcement agencies and crisis management services (Anand, 2018; Farsang et al., 2013). If an agricultural pathogen is introduced into a country, regardless of how and why, the response must be quick to contain the disease (EU, 2016a; Gamliel & Fletcher, 2017a). For some pathogens, the contingency plans for control measures are laid out by EU directives, while for others they are developed on a national level. To reduce the likelihood of disease spread, authorities can, for example, set up zones around an infected holding where animal, plant, vehicle, and equipment movements are restricted (European Commission, 2020c). During an outbreak, and depending on its nature and extent, collaboration with and assistance from others, such as police, customs, transportation authorities, food authorities, and county and municipalities, are needed to contain the disease. An efficient response requires that all actors are prepared to work collaboratively, and that good relationships and communication mechanisms between law enforcement, and plant, animal and human health officials are developed before an incident occurs (FBI, 2008; CDC, 2011; Thelaus et al., 2017; Anand, 2018). It is important to test agricultural disease contingency plans, regularly, through exercises involving these authorities.

2.5 Step V—Reporting

The fifth step in a risk and vulnerability analysis describes the work process. It includes who participated in the work, what sources of information were used, and their reliability. This step is important for future analyses and revisions. It is preferably described in the beginning of a written report, even if it cannot be completed before the completion of steps I-IV (Winehav & Nevhage, 2011).

The number of risks is immense, even within a limited function for society, and quantifications are required for prioritizing potential mitigation strategies (Robb, 2017). When there is a lack of data behind an analysis, as when analysing a potential agroterror event, only likelihoods with high uncertainty and estimated frequencies can be presented. The uncertainty of the likelihood and how to address it, needs to be communicated. The prospects of the recipients understanding the results increases if descriptions and quantifications of risks and consequences are uniform and if communication is targeted to different end user groups (Utne et al., 2008; Gilioli et al., 2017; EFSA PLH Panel et al., 2018; Månsson et al., 2019; Lin et al., 2017; Rydmark et al., 2020).

2.6 Step VI—Communication and continuation

The last step in the FORSA framework is where risk management actions identified in previous steps are evaluated and feed-back is given. This leads to decisions about how to proceed within the function for society, the use and communication of results to stakeholders, what actions to take and their implementation in order to minimize risks for unwanted events and mitigate those that may occur. To ensure that results are transferred, and actions are taken, assignments and responsibilities are given to named persons or organizations. The decisions and actions in step VI are valuable for step I in future analyses of the same or related functions.

A complicating factor in the case of an unintentional or agroterror event is that several actors will work in parallel. Plant or animal health authorities will manage the disease outbreak, diagnose and confirm its cause, determine its origin and thereby assist the law enforcement authorities in the identification of the perpetrator (Lewis et al., 2020). Simultaneously, security and law enforcement authorities will investigate criminal or terror implications. Public health authorities will also be involved if an attack is carried out using a zoonotic agent or a toxin-producing plant pathogen. The effectiveness of often-overlapping investigations could be limited by differences in cultures of information sharing and performance of work tasks, legal hurdles, vocabulary and definitions, and poor communication and understanding between agricultural health, public health, and law enforcement officials. This could lead to prolonged disease outbreaks or failures to gather evidence to identify and prosecute a perpetrator (CDC, 2011; Knutsson et al., 2012).

To build trust and improve working relationships and understanding between those who would be involved in the event of an agroterror attack, people from intelligence, law enforcement, diagnostic laboratory networks, public, animal and plant health could be brought together in seminars, workshops, collective improvisations, and table-top exercises (Frykmer et al., 2018; Lindberg & Melin, 2016; Mårtensson et al., 2013; Stack et al., 2014). All efforts to promote inter-agency cooperation, such as functioning communication, understanding of differences in work routines, and clarified expectations, are necessary when managing acts of agroterrorism and biohazard events. At the international level, there are initiatives for capacity building. A good example of efforts to improve resilience to agroterrorism is the OIE-FAO-INTERPOL project containing the bio-threat detection module SET (Vasconcelos Gioia et al., 2021).

3 Other frameworks or approaches for risk and vulnerability analysis

The overall goal with a risk and vulnerability analysis is to understand the nature of risks, strengthen crisis preparedness, reduce vulnerabilities, and increase the abilities to manage crises (Winehav & Nevhage, 2011). There are often separate analytical frameworks and models for risk analysis, and vulnerability. Analytic and conceptual vulnerability models are tools for understanding hazards and identifying risk management approaches (Fontaine & Steinemann, 2009; Luers et al., 2003; Turner et al., 2003).

The analytical frameworks described in Fig. 5 have similar structures and are applicable to agricultural production. Their differences seem larger due to the labelling of the steps. An analysis of the activities in individual steps may show more similarities. The largest differences are

whether the frameworks are cyclic, if and how the function for society (I) is addressed, and how reporting and communication (VI) take place. While some are shown as a linear flow (e.g., van Tuyll, 2013; Gamliel et al., 2017b), it should not imply an absence of feed-back of outcomes or experiences for the following event. Cyclic frameworks imply an ongoing process with built-in learning components. Several disciplines will be involved in a risk and vulnerability analysis and most of the frameworks presented here have built-in flexibility to manage this, as well as to include new actors or components in an ongoing analysis.

The frameworks presented by the World Organisation for Animal Health (OIE) and International Plant Protection Convention (IPPC) are informative concerning the risks for animals and plants (IPPC, 2007; OIE, 2019). Their advantage is the use of globally agreed standards for risk analysis.

FORSA ^A	FAO ^B	ISO ^C	Risk management framework ^D	Unifed framework ^E	Dutch National Security strategy ^F	All-hazards framework ^G
Function for society (I)		Scope, context and criteria	Prevention	Function identification and system definition	N/A	Scenario, identification
Unwanted event (II)	Preliminary risk management activities		Detection	Identification of sources of threats	Threat/Risk analysis	Security vulnerability assessment
Analysis of event (III)		Risk assessment (identification, analysis and evaluation)	Diagnosis	Uncertainty analysis		
	Identification and selection of risk management options		Risk assessment	Consequence analysis	Risk assessment	Hazard likelihood assessment
Actions (IV)	Implementation of control measures	Risk treatment	Containment eradication	Describe and evaluate risks/vulnerabilities	Task capabilities	Risk assessment
				Identification of measures and loop back to source identification	Policy initiatives	Benefit/cost analysis of proposed counter measures
Reporting (V)		Recording and reporting		N/A	N/A	N/A
	Monitoring and review		Management and recovery			
Communication and continuation (VI)		Communication, consulting, monitoring and review (continuous)		N/A	N/A	N/A

Fig. 5 Comparisons of analytical frameworks for risk and vulnerability analysis or risk management. Steps in individual frameworks are placed in relation to how they are interpreted in comparison with steps I-VI in the FORSA framework (A) (Winehav & Nevhage, 2011). **B:** The FAO’s generic Risk management framework (FAO, 2007) is cyclic. It is focused on risk management and less on the identification of unwanted events in the function for society of concern. **C:** The risk management guidelines by ISO (Anon, 2018) are aimed for managing risks by building risk management frameworks in organizations. It is a circular framework, and an example of where

risk analysis is described as part of the risk assessment. **D:** The risk management framework for plant biosecurity describes in eight steps the activities and responsibilities in the management process following an outbreak in ‘real time’ (Gamliel et al., 2017b). **E and F:** Risk and vulnerability analyses are also found in engineering sciences (Aven, 2007) and in the Dutch National Security Strategy (van Tuyll, 2013). **G:** A common analytical framework developed for benefit cost analysis in risk assessments by Ayyub et al. (2007), addresses the importance of quantifications and inclusion of interdependencies in complex systems. Created with [BioRender.com](https://www.biorender.com)

These frameworks have three steps 1) *Hazard identification*, 2) *Risk assessment*, and 3) *Risk management*, using the OIE terminology. Communication is continuous as in the ISO framework (Anon, 2018). The socioeconomic impacts are included, i.e., benefit cost analyses of the alternatives for risk mitigation. For analysis of unwanted events in steps I-III of the FORSA framework, it is worth considering using the outlines from IPPC and OIE.

Unlike some of the analytical frameworks for risk and vulnerability analysis, the FORSA approach is proactive. It starts by describing the function for society at risk instead of with the unwanted event. It provides background and helps to identify possible unwanted events by scrutinizing the function itself. The circular structure aids in developing action plans and strengthens the ability to handle and prepare for crises. With the built-in feedback loop, the learning outcome from one analysis feeds into, and facilitates, a recurring one. A stronger focus may be placed on specific steps, depending on the overall aim of the analysis, and returns to previous steps are possible. In a FORSA risk and vulnerability analysis, several predefined scales and assessment criteria are used, and the sources of information and uncertainties of the assessments are reported. The systems that typically are analysed with this framework are more narrowly defined than the system addressed in this review.

4 Final remarks

If the societal costs of crop and animal diseases were acknowledged, this information could justify direction of more resources for surveillance and action plans to manage serious events. In general, plant disease management has a lower public profile than animal health (Ilbery et al., 2012; Waage & Mumford, 2008; Wilkinson et al., 2011). Animals also represent a higher investment value than annual crops (Waage & Mumford, 2008). The effects and consequences of an unwanted event within agricultural primary production would vary depending on *i*) whether it is accidental or intentional, *ii*) the magnitude of the damage, *iii*) the capability to maintain production capacity of the affected commodity and ensure food security, and *iv*) the extent of the outbreak when detected. Clearly structured frameworks are useful for analysing unwanted events, their effects and what actions that would be required for reducing their damage. Here we used the FORSA framework as one approach to analyse threats to animal and crop production in agriculture.

A risk and vulnerability analysis that addresses activities within agricultural production soon becomes multidisciplinary. Even an analysis of a narrowly defined function

within agricultural production, covers several disciplines, involving farmers, local and national authorities (including police and customs), plant and animal health experts, politicians, and legislators. The drivers for emergence of new pathogens need to be identified and analysed on a multi-disciplinary scale (Anand, 2018; Richardson et al., 2016). Due to this complexity, a systems approach is required in the risk and vulnerability analysis itself and in all decisions (political, practical, legislative) concerning risk management. As an example, the BSE crisis, during 1988–2012 with a feed-transmitted epidemic in cows and zoonotic transfer to humans (variant Creutzfeldt-Jakob disease) through contaminated beef or beef products (Salman et al., 2012), showed that a systems approach was necessary to capture all the complexities that challenged the control efforts.

Multidisciplinary involves the challenge of differences in the professional languages within the group working with a risk and vulnerability analysis. Working through the steps in a well-structured framework facilitates the mutual understanding, and abilities to communicate between disciplines. The understanding of terms, definitions, organizational structures, and differences in working cultures would be promoted by active efforts to improve inter-agency collaboration. All actors should be familiar with the individual steps in analyses and assessments at the onset of the work process, and an ideal way of testing management strategies and inter-agency collaboration is to have real-time exercises (Knutsson, 2017; Mackelprang & Friedman, 2021).

Communication that fails when facing a real biohazard could create more problems than the hazard itself. As an example, the police and customs, and national control agencies need the capability to identify and investigate agroterrorism crime as well as negligence of regulations. There may be a lack of impetus for further improvements, since few events have been linked to agroterrorism, and it could be difficult to maintain a certain alert level if the events are rare.

To improve the preparedness and ability to manage both natural and intentional biohazards, risk management options include bolstering farm-level biosecurity, increasing laboratory capacity, and developing and improving methods for diagnosis and early detection. For a country to be better prepared, agroterrorism or biohazard scenarios should be included in disease risk analyses, and inter-agency communication enhanced. There is a need for willingness and motivation to allocate resources, and actions to improve national appreciation for domestic agricultural production.

There will always be a demand for personnel with the special skills to identify pathogens and diagnose diseases. This emphasizes the need to maintain high levels in education and regular training of personnel. Education in fundamental elements, such as in-field or on-farm disease

diagnosis, pathogen biology and disease epidemiology, should include the ability to handle exotic diseases, disasters and agroterrorism (Chomel & Marano, 2009; Dunning et al., 2009; Fletcher et al., 2020; Kelly, 2005; MacDonald et al., 2009; Mackelprang & Friedman, 2021).

There is a need for openness for unexpected events. One can prepare for the emergence of new plant and animal diseases, zoonoses, and pandemics, but not predict when and where they will appear (Meslin, 1997; Webster & Walker, 2003; WHO, 2004; Ali et al., 2017). Taking the expected behaviour of other plant and animal pathogens for granted may come with surprises, as will the effects of climate change (Shaw & Osbourne, 2011; Casadevall, 2017; Garret et al., 2021). With the Covid-19 pandemic, war in Ukraine and persistent global supply chain problems during 2020–2022, the context for risk and vulnerability analyses exemplified by the FORSA framework has become more complicated. We foresee more difficulties with the supply of necessary inputs in agriculture, but also food processing, including supply disruptions of pesticides, fertilizers, minerals and vitamins. The Ukraine war is associated with more expensive and uncertain supplies of cereals and inputs such as fertilizers.

The risk of an agroterror attack is low but not negligible. However, the potential for agroterror events will increase as the 4th industrial revolution technologies are implemented in agriculture (e.g., Koblenz, 2020). These technological systems may advance digitization processes, be commercially available and able to be repurposed for malicious use (e.g., Bajema, 2018). Major economic fallout is foreseen as a result of an agroterrorist act. Other consequences include erosion of public trust in government to protect national security and provide safe food and increased public health costs. Human lives could also be at risk if the chosen pathogen is zoonotic or produces toxin.

We conclude that agroterrorism must be included when threats to society are considered. Our food supply chain becomes more fragile with more unknowns, thereby

increasing the needs for risk and vulnerability analyses of which FORSA is one example. European countries have strong agricultural protection systems in place and coupled with efficient diagnostic laboratory networks, these can respond to natural emergencies of crop and livestock diseases. There are, however, several areas where improvements could be made to enhance the level of preparedness for both natural and intentional spread of pathogens. Although biased towards Europe and conditions in the EU, the principles presented here have applications world-wide.

Annex 1 Characteristics of agroterrorism agents

In order to be considered a major threat for antagonistic use pathogens must possess certain characteristics*:

- Pathogenic for livestock, poultry, or food crops
- Highly infectious and contagious in the target population
- Easy to acquire or produce
- Easy to disseminate
- Good ability to survive in the environment
- Low level of immunity in the target population
- Produces a predictable pattern of clinical disease in the target population
- Attributable to a natural outbreak, ensuring plausible deniability
- Not harmful to the perpetrator
- Produces extremely negative biological, social and/or economic effects
- Used in previous attacks or previously developed as part of bioweapons program

*Summarized from: Wilson et al., 2000; Clarke & Rinderknecht, 2011; Menrath et al., 2014.

Annex 2 Examples of pathogens that constitute serious threats to food security

Pathogen	Disease	Host	Areas or countries	References
<i>Puccinia graminis</i> f.sp. <i>tritici</i>	Stem rust (Black rust)	Wheat	Worldwide	Meyer et al., 2017; Hovmøller et al., 2022
<i>Puccinia striiformis</i> f.sp. <i>tritici</i>	Yellow rust (Stripe rust)	Wheat	Worldwide	Hovmøller et al., 2016; Ali et al., 2017; Carmona et al., 2019
<i>Xylella fastidiosa</i>	Leaf scorch	Olive, almond	S. Europe	Pautasso et al., 2015; Martelli et al., 2016; Schneider et al., 2020; EFSA, 2020a; European Commission, 2020b; Landa et al., 2020
<i>Magnaporthe oryzae</i>	Wheat blast	Wheat	South America, Bangladesh, Zambia	Chowdhury et al., 2017; Ceresini et al., 2018; Islam et al., 2020; Tembo et al., 2020
<i>Fusarium odoratissimum</i> Tropical race 4	Panama disease	Banana	Africa, Colombia – South and Latin America	Ordóñez et al., 2015; Maryani et al., 2019; García-Bastidas et al., 2020
Sri Lankan cassava mosaic virus (SLCMV)	Cassava mosaic disease (CMD)	Cassava	Asia	Minato et al., 2019; Jones, 2020; Siriwan et al., 2020
African swine fever virus (ASFV)	African swine fever (ASF)	Wild and domestic pigs	Africa, Eastern and Central Europe, Asia	Beltrán-Alcrudo et al., 2008; Stokstad, 2017; BBC, 2019; Halasa et al., 2019; Gavier-Widen et al., 2020
Avian influenza virus (AIV)	Avian influenza (AI)	Poultry	Worldwide	Alexander, 2000; Spackman, 2020
Lumpy skin disease virus (LSDV)	Lumpy skin disease (LSD)	Cattle	Middle East, Southeast Europe	EFSA et al., 2020c
Congo Crimean haemorrhagic fever virus (CCHFV)	Congo Crimean haemorrhagic fever (CCHF)	Cattle, sheep, goats	Africa, Endemic in the Balkans, Bulgaria, Spain	EFSA AHAW Panel, More et al., 2017a
Rift Valley fever virus (RVFV)	Rift Valley fever (RVF)	Cattle, sheep, goats	Africa, the Arabian Peninsula	EFSA AHAW Panel et al., 2020

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Declarations

Conflicts of interest The authors declared that they have no conflicts of interest.

Research involving human and animal rights Data involving human or animal subjects are present in publications and other publicly available sources.

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References

- Abson, D. J. (2019). The economic drivers and consequences of agricultural specialization. In G. Lemaire, P. C. De Faccio Carvalho, S. Kronberg, & S. Recous (Eds.), *Agroecosystem diversity* (pp. 301–315). Elsevier.
- Alexander, D. J. (2000). A review of avian influenza in different bird species. *Veterinary Microbiology*, *74*, 3–13. [https://doi.org/10.1016/S0378-1135\(00\)00160-7](https://doi.org/10.1016/S0378-1135(00)00160-7).
- Ali, S., Rodriguez-Algaba, J., Thach, T., Sørensen, C. K., Hansen, J. G., Lassen, P., et al. (2017). Yellow rust epidemics worldwide were caused by pathogen races from divergent genetic lineages. *Frontiers in Plant Science*, *8*, 1057. <https://doi.org/10.3389/fpls.2017.01057>.
- Alshannaq, A., & Yu, J.-H. (2017). Occurrence, toxicity and analysis of major mycotoxins in food. *International Journal of Environmental Research and Public Health*, *14*(6), 632–652.
- Anand, M. (2018). A systems approach to agricultural biosecurity. *Health Security*, *16*, 58–68. <https://doi.org/10.1089/hs.2017.0035>.
- Anon. (2018). *Risk management — Guidelines*. ISO 31000:2018. www.iso.org/obp/ui/#iso:std:iso:31000:ed-2:v1:en
- Arezki, R., & Brückner, M. (2011). Food Prices and Political Instability. *IMF Working Paper* 11/62. IMF, Washington, USA. www.imf.org/external/pubs/ft/wp/2011/wp1162.pdf
- Atlas, R. M., & Dando, M. (2006). The dual-use dilemma for the life sciences: Perspectives, conundrums and global solutions. *Biosecurity and Bioterrorism: Biodefense Strategy, Practice, and Science*, *4*(3), 276–286.
- Australia Group. (2007). *Fighting the spread of chemical and biological weapons. Strengthening global security*. 20 pp. www.australiagroup.net/en/index.html
- Aven, T. (2007). A unified framework for risk and vulnerability analysis covering both safety and security. *Reliability Engineering and System Safety*, *92*, 745–754.
- Ayyub, B. M., McGill, W. L., & Kaminskiy, M. (2007). Critical Asset and Portfolio Risk Analysis: An All-Hazards Framework. *Risk Analysis*, *27*(4), 789–801. <https://doi.org/10.1111/j.1539-6924.2007.00911.x>.
- Bajema, N.E. (2018). WMD in the Digital Age: Understanding the Impact of Emerging Technologies. *Emergence and Convergence*, Research paper No. 4. Oct. 2018. 34 pp.
- BBC News. (2019). Denmark builds anti-pig border fence amid swine fever fears. January 29, 2019. *BBC News website*. www.bbc.com/news/world-europe-47027582
- Becker, S. M. (2010). Social, psychological, and communications impacts of an agroterrorism attack. In J. G. Voeller (Ed.), *Wiley Handbook of Science and Technology for Homeland Security* (pp. 1653–1668). John Wiley and Sons Inc.
- Beltrán-Alcrudo, D., Lubroth, J., Depner, K., & De La Rocque, S. (2008). African swine fever in the Caucasus. *FAO Empress watch*, April 2008. 8 pp. www.fao.org/3/a-aj214e.pdf
- Blake, A., Sinclair, M. T., & Sugiyarto, G. (2003). Quantifying the impact of foot and mouth disease on tourism and the UK economy. *Tourism Economics*, *9*, 449–465.
- Burger, R. (2012). HEC O104:H4 in Germany 2011: Large Outbreak of Bloody Diarrhea and Haemolytic Uraemic Syndrome by Shiga Toxin–Producing *E. coli* via Contaminated Food. In: IOM (Institute of Medicine). *Improving food safety through a One Health approach*. Washington, DC: The National Academies Press. Pp. 115–130.
- Carmona, M. A., Sautua, F. J., Pérez-Hernández, O., Grosso, C., Vettorello, L., Milanese, B., et al. (2019). Rapid emergency response to yellow rust epidemics caused by newly introduced lineages of *Puccinia striiformis* f. sp. *tritici* in Argentina. (2019). *Tropical Plant Pathology*, *44*, 385–391. <https://doi.org/10.1007/s40858-019-00295-y>.
- Carus, W. S. (1998). *Bioterrorism and Biocrimes. The Illicit Use of Biological Agents Since 1900*. Working paper. Revised Aug. 2001. Center for Counterproliferation Research National Defense University Washington, D.C. 209 pp.
- Carvajal-Yepes, M., Cardwell, K., Nelson, A., Garrett, K. A., Giovani, B., Saunders, D. G. O., et al. (2019). A global surveillance system for crop diseases. *Science*, *364*(6447), 1237–1239. <https://doi.org/10.1126/science.aaw1572>.
- Casadevall, A. (2017). Don't Forget the Fungi When Considering Global Catastrophic Biorisks. *Health Security*, *15*(4), 341–342. <https://doi.org/10.1089/hs.2017.0048>.
- CDC (Centers for Disease Control). (2011). *Criminal and Epidemiological Investigation Handbook*. Available from: www.cdc.gov/php/docs/crimepihandbook2011.pdf
- Centner, T. J., & Ferreira, S. (2012). Ability of governments to take actions to confront incursions of diseases – a case study: Citrus canker in Florida. *Plant Pathology*, *62*, 821–828.
- Ceresini, P. C., Castroagudín, V. L., Fabrício Rodrigues, F. A., Rios, J. A., Aucique-Pérez, C. E., Moreira, S. I., et al. (2018). Wheat Blast: Past, Present, and Future. *Annual Review of Phytopathology*, *56*, 427–456. <https://doi.org/10.1146/annurev-phyto-080417-050036>.
- CFIA (Canadian Food Inspection Agency). (2013). National farm-level biosecurity planning guide – proactive management of plant resources. www.inspection.gc.ca/plants/plant-pests-invasive-species/biosecurity/guide/eng/1323477130171/1323477259986#ctma
- Chalk, P. (2004). *Hitting America's soft underbelly: The potential threat of deliberate biological attacks against the U.S. agricultural and food industry*. Santa Monica, CA: RAND Corporation. www.rand.org/pubs/monographs/MG135.html
- Chalk, P. (2010). Vulnerability of the domestic food supply chain. In J. G. Voeller (Ed.), *Wiley Handbook of Science and Technology for Homeland Security* (pp. 1625–1635). John Wiley and Sons Inc.
- Chomel, B. B., & Marano, N. (2009). Essential veterinary education in emerging infections, modes of introduction of exotic animals, zoonotic diseases, bioterrorism, implications for human and animal health and disease manifestation. *Revue Scientifique Et Technique*, *28*(2), 559–565.
- Chowdhury, A. K., Saharan, M. S., Aggrawal, R., Malaker, P. K., Barma, N. C. D., Tiwari, T. P., et al. (2017). Occurrence of wheat blast in Bangladesh and its implications for South Asian wheat production. *Indian Journal of Genetics*, *77*, 1–9. <https://doi.org/10.5958/0975-6906.2017.00001>.
- Clarke, N. P., & Rinderknecht, J. L. (2011). Bioterrorism – intentional introduction of animal disease. *Revue Scientifique Et Technique*, *30*(1), 131–138.
- Conraths, F. J., Gethmann, J. M., Staubach, C., Mettenleiter, T. C., Beer, M., & Hoffmann, B. (2009). Epidemiology of bluetongue virus serotype 8, Germany. *Emerging Infectious Diseases*, *15*, 433–435.
- Crutchley, T. M., Rodgers, J. B., Whiteside, J. P., Jr, Vanier, M., & Terndrup, T. E. (2007). Agroterrorism: Where are we in the ongoing war on terrorism? *Journal of Food Protection*, *70*(3), 791–804.
- Cupp, O. S., Walker II, D. E., & Hillison, J. (2004). Agroterrorism in the U.S.: key security challenge for the 21st century. *Biosecurity*, *2*(2): 97–105.
- DiEuliis, D., Berger, K., & Gronvall, G. (2017). Biosecurity implications for the synthesis of Horsepox, an Orthopoxvirus. *Health Security*, *15*(6), 629–637.
- Dithmer, J., & Abdulai, A. (2017). Does trade openness contribute to food security? A dynamic panel analysis. *Food Policy*, *69*, 218–230.
- Dorea, F., Nöremark, M., Widgren, S., Frössling, J., Boklund, A., Halasa, T., & Ståhl, K. (2017). Evaluation of strategies to control a potential outbreak of Foot-and-mouth disease in Sweden. *Frontiers of Veterinary Science*, *4*, 118.

- Drew, T. W., & Mueller-Doblies, U. U. (2017). Dual use issues in research – a subject of increasing concern? *Vaccine*, *35*, 5990–5994.
- Dunn, M. V. (1999). The threat of bioterrorism to U.S. agriculture. *Annals of the New York Academy of Sciences*, *894*, 184–188.
- Dunning, D., Martin, M. P., Tickel, J. L., Gentry, W. B., Cowen, P., & Slenning, B. D. (2009). Preparedness and disaster training for veterinary students: Literature review and description of the North Carolina State University Credentialed Veterinary Responder Program. *Journal of Veterinary Medical Education*, *36*(3), 317–330.
- EFSA (European Food Safety Authority). (2020a). Scientific report on the update of the *Xylella* spp. host plant database – systematic literature search up to 30 June 2019. *EFSA Journal*, *18*(4), 6114, 61 pp. <https://doi.org/10.2903/j.efsa.2020a.6114>
- EFSA (European Food Safety Authority), Lázaro, E., Parnell, S., Vicent Civera, A., Schans, J., Schenk, M., Abrahantes, J. C., Zancanaro, G., & Vos, S. (2020b). General guidelines for statistically sound and risk-based surveys of plant pests. EFSA supporting publication 2020b:EN-1919. 65 pp. <https://doi.org/10.2903/sp.efsa.2020b.EN-1919>
- EFSA (European Food Safety Authority), Calistri, P., De Clercq, K., Gubbins, S., Klement, E., Stegeman, A., Cortinas Abrahantes, J., Marojevic, D., Antoniou, S. E., & Broglia, A. (2020c). Scientific report on the lumpy skin disease epidemiological report IV: data collection and analysis. *EFSA Journal*, *18*(2), 6010, 36 pp. <https://doi.org/10.2903/j.efsa.2020c.6010>
- EFSA AHAW Panel (EFSA Panel on Animal Health and Welfare), More, S., Bicout, D., Bøtner, A., Butterworth, A., Calistri, P., De Koeijer, A., Depner, K., Edwards, S., Garin-Bastuji, B., Good, M., Gortazar Schmidt, C., Michel, V., Miranda, M. A., Nielsen, S.S., Raj, M., Sihvonen, L., Spoolder, H., Thulke, H. H., Velarde, A., Willeberg, P., Winckler, C., Bau, A., Beltran-Beck, B., Carnesecchi, E., Casier, P., Czwienczek, E., Dhollander, S., Georgiadis, M., Gogin, A., Pasinato, L., Richardson, J., Riolo, F., Rossi, G., Watts, M., Lima, E., & Stegeman, J. A. (2017a). Scientific opinion on vector-borne diseases. *EFSA Journal* *15*(5), 4793, 91 pp. <https://doi.org/10.2903/j.efsa.2017a.4793>
- EFSA AHAW Panel (EFSA Panel on Animal Health and Welfare), Nielsen, S.S., Alvarez, J., Bicout, D. J., Calistri, P., Depner, K., Drewe, J. A., Garin-Bastuji, B., Gonzales Rojas, J. L., Gortazar Schmidt, C., Herskin, M., Michel, V., Miranda Chueca, M. A., Pasquali, P., Roberts, H. C., Sihvonen, L. H., Stahl, K., Calvo, A. V., Viltrop, A., Winckler, C., Gubbins, S., Antoniou, S. E., Broglia, A., Abrahantes, J. C., Dhollander, S., & Van der Stede, Y. (2020). Scientific Opinion on Rift Valley Fever – assessment of effectiveness of surveillance and control measures in the EU. *EFSA Journal*, *18*(11), 6292, 75 pp. <https://doi.org/10.2903/j.efsa.2020.6292> ISSN: 1831–4732
- EFSA PLH Panel (EFSA Panel on Plant Health), Jeger, M., Bragard, C., Caffier, D., Candresse, T., Chatzivassiliou, E., Dehnen-Schmutz, K., Grégoire, J. C., Jaques Miret, J. A., MacLeod, A., Navajas Navarro, M., Niere, B., Parnell, S., Potting, R., Rafoss, T., Rossi, V., Urek, G., Van Bruggen, A., Van Der Werf, W., West, J., Winter, S., Hart, A., Schans, J., Schrader, G., Suffert, M., Kertész, V., Kozelska, S., Mannino, M.R., Mosbach-Schulz, O., Pautasso, M., Stancanelli, G., Tramontini, S., Vos, S., & Gilioli, G. (2018). Guidance on quantitative pest risk assessment. *EFSA Journal*, *16*(8), 5350, 86 pp. <https://doi.org/10.2903/j.efsa.2018.5350>
- Elbers, A., & Knutsson, R. (2013). Agroterrorism targeting livestock: A review with a focus on early detection systems. *Biosecurity and Bioterrorism: Biodefense Strategy, Practice, and Science*, *11*(Suppl), S25–S35.
- Elbers, A. R. W., Gorgievski-Duijvesteijn, M. J., van der Velden, P. G., Loeffen, W. L. A., & Zarafshani, K. (2010). A socio-psychological investigation into limitations and incentives concerning reporting a clinically suspect situation aimed at improving early detection of classical swine fever outbreaks. *Veterinary of Microbiology*, *142*, 108–118.
- Elworth, R. A. L., Diaz, C., Yang, J., de Figueiredo, P., Ternus, K., & Treangen, T. (2020). Synthetic DNA and biosecurity: Nuances of predicting pathogenicity and the impetus for novel computational approaches for screening oligonucleotides. *PLoS Pathogens*, *16*(8). <https://doi.org/10.1371/journal.ppat.1008649>.
- EPPO (European and Mediterranean Plant Protection Organization). (2020). *EPPO A1 and A2 lists of pests recommended for regulation as quarantine pests*. www.eppo.int/media/uploaded_images/RESOURCES/eppo_standards/pm1/pm1-002-29-en.pdf
- EU. (2002). Regulation (EC) no 178/2002 of the European Parliament and of the Council of 28 January 2002 laying down the general principles and requirements of food law, establishing the European Food Safety Authority and laying down procedures in matters of food safety. 24 pp. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32002R0178&from=EN>
- EU. (2009). Regulation (EC) No 1107/2009 of the European Parliament and of the Council of 21 October 2009 concerning the placing of plant protection products on the market. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009R1107&from=EN>
- EU. (2016a). Regulation (EU) 2016a/429 of the European Parliament and of the Council of 9 March 2016a on transmissible animal diseases and amending and repealing certain acts in the area of animal health ('Animal Health Law'), 208 pp.
- EU. (2016b). Regulation (EU) 2016b/2031 of the European Parliament of the Council of 26 October 2016b on protective measures against pests of plants. 101 pp.
- EU. (2017). Regulation (EU) 2017/625 of the European Parliament and of the Council of 15 March 2017 on official controls and other official activities performed to ensure the application of food and feed law, rules on animal health and welfare, plant health and plant protection products, 142 pp. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32017R0625>
- EU. (2019). Commission delegated Regulation (EU) 2019/1702 of 1 August 2019 supplementing Regulation (EU) 2016/2031 of the European Parliament and of the Council by establishing the list of priority pests. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R1702&from=EN>
- European Chemicals Agency. (2021). *List of approved active substances*. <https://echa.europa.eu/regulations/biocidal-products-regulation/approval-of-active-substances/list-of-approved-active-substances>
- European Commission. (2008). Working Document on the Task Force on Animal Disease Surveillance European Commission, Health & Consumers Directorate-General, Directorate D – Animal Health and Welfare, Unit D1 – Animal Health and Standing Committees. https://ec.europa.eu/food/sites/food/files/animals/docs/ad_surveillance_tfads_wrk-doc.pdf
- European Commission. (2012). Commission implementing decision of 27 November 2012 amending Annexes I and II to Council Directive 82/894/EEC on the notification of animal diseases within the Community. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012D0737&from=EN>
- European Commission. (2013). Structure and dynamics of EU farms: changes, trends and policy relevance. EU Agricultural Economics Brief No. 9, Directorate-General for Agriculture and Rural Development. https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/farming/documents/agri-economics-brief-09_en.pdf
- European Commission. (2018a). Common agricultural policy. https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy_en.
- European Commission. (2018b). Commission delegated regulation (EU) 2018b/631 of 7 February 2018b supplementing Regulation

- (EU) 2017/625 of the European Parliament and of the Council by establishing European Union reference laboratories for pests of plants. 2 pp. <https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32018R0631>
- European Commission. (2020a). Commission implementing regulation (EU) 2019/2072 of 28 November 2019 establishing uniform conditions for the implementation of Regulation (EU) 2016/2031 of the European Parliament and the Council, as regards protective measures against pests of plants, and repealing Commission Regulation (EC) No 690/2008 and amending Commission Implementing Regulation (EU) 2018/2019. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02019R2072-20210101&from=EN>
- European Commission. (2020b). Commission implementing regulation (EU) 2020b/1201 of 14 August 2020b as regards measures to prevent the introduction into and the spread within the Union of *Xylella fastidiosa* (Wells *et al.*). <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32020bR1201>
- European Commission. (2020c). Commission delegated regulation (EU) 2020c/687 of 17 December 2019 supplementing Regulation (EU) 2016/429 of the European Parliament and the Council, as regards rules for the prevention and control of certain listed diseases. 76 pp. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32020cR0687>
- Eurostat. (2018). Agriculture, forestry and fishery statistics. 2020 edition. <https://doi.org/10.2785/340432>. <https://ec.europa.eu/eurostat/documents/3217494/9455154/KS-FK-18-001-EN-N.pdf/a9ddd7db-c40c-48c9-8ed5-a8a90f4faa3f>
- Evans, B. (2006). The social and political impact of animal diseases. *Vet Ital*, 42(4), 399–406.
- FAO. (2007). *FAO Biosecurity toolkit* (p. 140). Food and Agriculture Organization of the United Nations.
- FAO. (2016). *Economic analysis of animal diseases*. FAO Animal Production and Health Guidelines. No. 18. Rome. www.fao.org/3/a-i5512e.pdf
- Farsang, A., Frentzel, H., Kulcsar, G., & Soos, T. (2013). Control of the deliberate spread of Foot-and-mouth disease virus. *Biosecurity and Bioterrorism: Biodefense Strategy, Practice, and Science*, 11(Suppl 1), S115–S122.
- FBI (Federal Bureau of Investigation). (2008). *Criminal Investigation Handbook for Agroterrorism*. www.fsis.usda.gov/wps/wcm/connect/c3ca6715-f7d4-46be-8ae1-f94be7e83786/Investigation_Handbook_Agroterrorism.pdf?MOD=AJPERES
- Fletcher, J., Gamliel, A., Gullino, M. L., McKirdy, S. J., Smith, G. R., & Stack, J. P. (2020). A fresh look at graduate education in Plant Pathology in a changing world: Global needs and perspectives. *Journal of Plant Pathology*, 102(5), 609–618. <https://doi.org/10.1007/s42161-020-00509-2>.
- Fletcher, J., Alpas, H., Henry, C. M., Haynes, E., Dehne, H. W., Ma, L. M., *et al.* (2017). Vulnerabilities, threats and gaps in food biosecurity. In M. L. Gullino, J. P. Stack, J. Fletcher, & J. D. Mumford (Eds.), *Practical Tools for Plant and Food Biosecurity: Results from a European Network of Excellence* (pp. 61–75). Springer International Publishing, Cham.
- Fontaine, M. M., & Steinemann, A. C. (2009). Assessing vulnerability to natural hazards: Impact-based method and application to drought in Washington state. *Natural Hazards Review*, 10(1), 11–18. [https://doi.org/10.1061/\(ASCE\)1527-6988](https://doi.org/10.1061/(ASCE)1527-6988).
- FoodDrinkEurope. (2020). Data & trends. EU food industry, Edition 2020. 31 pp. www.fooddrinkeurope.eu/uploads/publications_documents/FoodDrinkEurope_-_DataTrends2020_digital.pdf
- Fox, J. A., & Peterson, H. H. (2002). Bovine Spongiform Encephalopathy (BSE): Risks and implications for the United States. *Proceedings of the NCCC-134 Conference on Applied Commodity Price Analysis, Forecasting and Market Risk Management*. St Louis, Missouri. www.farmdoc.illinois.edu/nccc134/conf_2002/pdf/confp22-02.pdf
- Foxell, J. W., Jr. (2001). Current trends in agroterrorism (antilivestock, anticrop and antisoil bioagricultural terrorism) and their potential impact on food security. *Studies in Conflict and Terrorism*, 24, 107–129. <https://doi.org/10.1080/10576100151101623>.
- Frykmer, T., Uhr, C., & Tehler, H. (2018). On collective improvisation in crisis management – A scoping study analysis. *Safety Science*, 110, 100–109.
- Gamliel, A., & Fletcher, J. (2017). Containment and eradication of invasive pathogens. In M. L. Gullino, J. P. Stack, J. Fletcher, & J. D. Mumford (Eds.), *Practical Tools for Plant and Food Biosecurity: Results from a European Network of Excellence* (pp. 243–256). Springer International Publishing, Cham.
- Gamliel, A., Stack, J. P., & Mumford, J. D. (2017b). A risk management framework for plant biosecurity. In: Gullino, M.L., Stack, J.P., Fletcher, J., & Mumford, J.D. (Eds.). *Practical tools for plant and food biosecurity. Results from a European network of excellence*. Springer, Switzerland. 384 pp.
- García-Bastidas, F. A., Quintero-Vargas, J. C., Ayala-Vasquez, M., Schermer, T., Seidl, M. F., Santos-Paiva, M., *et al.* (2020). First report of Fusarium wilt Tropical Race 4 in Cavendish bananas caused by *Fusarium odoratissimum* in Colombia. *Plant Disease*, 104, 994. <https://doi.org/10.1094/PDIS-09-19-1922-PDN>.
- Garrett, K. A., Nita, M., De Wolf, E. D., Esker, P. D., Gomez-Montano, L., & Sparks, A. H. (2021). Plant pathogens as indicators of climate change. In: *Climate change* (3rd edition), Ed.: T.M. Letcher. p. 499–513. Elsevier. <https://doi.org/10.1016/B978-0-12-821575-3.00024-4>
- Gavriel-Widen, D., Ståhl, K., & Dixon, L. (2020). No hasty solutions for African Swine fever. *Science* 367(6478): 622–624. 07 Feb 2020. <https://doi.org/10.1126/science.aaz8590>
- Gethmann, J., Probst, C., & Conraths, F. J. (2020). Economic Impact of a Bluetongue Serotype 8 Epidemic in Germany. *Front Vet Sci*, 7, 65. <https://doi.org/10.3389/fvets.2020.00065>.
- Gilioli, G., Schrader, G., Grégoire, J.-C., MacLeod, A., Mosbach-Schulz, O., Rafoss, T., *et al.* (2017). The EFSA quantitative approach to pest risk assessment – methodological aspects and case studies. *Bulletin OEPP/EPPO Bulletin*, 47(2), 213–219. <https://doi.org/10.1111/epp.12377>.
- Gilligan, C. A. (2008). Sustainable agriculture and plant diseases: An epidemiological perspective. *Phil. Trans. r. Soc. B*, 363, 741–759. <https://doi.org/10.1098/rstb.2007.2181>.
- Green, S., Ellis, T., Jung, J., & Lee, J. (2017). Vulnerability, risk and agroterrorism: An examination of international strategy and its relevance for the Republic of Korea. *Crime Prev. Community Saf*, 19, 31–45.
- Greger, M. (2007). The long haul: Risks associated with livestock transport. *Biosecurity and Bioterrorism: Biodefense Strategy, Practice, and Science*, 5(4), 301–311.
- Gullino, M. L. (2009). Teaching Plant Pathology and Disease and Pest Management for University Students: Some Considerations After Thirty Years of Experience. *Arab J. Pl. Prot.*, 27(2), 233–235.
- Halasa, T., Boklund, A., Bøtner, A., Mortensen, S., & Kjær, L. J. (2019). Simulation of transmission and persistence of African swine fever in wild boar in Denmark. *Preventive Veterinary Medicine*, 167, 68–79. <https://doi.org/10.1016/j.prevetmed.2019.03.028>.
- Hammond, N. E. B., Hardie, D., Hauser, C. E., & Reid, S. A. (2016). Can general surveillance detect high priority pests in the Western Australian Grains Industry? *Crop Protection*, 79, 8–14.
- Higgins, V., Bryant, M., Hernández-Jover, M., Rast, L., & McShane, C. (2016). Devolved responsibility and on-farm biosecurity: Practices of biosecure farming care in livestock production. *Sociologia Ruralis*, 58, 20–39. <https://doi.org/10.1111/soru.12155>.
- Hossain, R., Menzel, W., Lachmann, C., & Varrelmann, M. (2021). New insights into virus yellows distribution in Europe and effects of beet yellows virus, beet mild yellowing virus, and

- beet chlorosis virus on sugar beet yield following field inoculation. *Plant Pathology*, 70, 584–593. <https://doi.org/10.1111/ppa.13306>.
- Hovmøller, M. S., Walter, S., Bayles, R. A., Hubbard, A., Flath, K., Sommerfeldt, N., et al. (2016). Replacement of the European wheat yellow rust population by new races from the centre of diversity in the near-Himalayan region. *Plant Pathology*, 65, 402–411.
- Hovmøller, M. S., Patpour, M., Rodriguez-Algaba, J., Randazzo, B., Villegas, D., Shamanin, V. P., Berlin, A., Flath, K., Czembor, P., Hanzalova, A., Sliková, S., Skolotneva, E. S., Jin, Y., Szabo, L., Meyer, K. J. G., Valade, R., Thach, T., Grønbech Hansen, J., & Fejer Justesen, A. (2022). Wheat stem rust back in Europe: Diversity, prevalence and impact on host resistance. *Frontiers in Plant Science* (accepted for publication).
- Hu, Y., Wilson, S., Schwessinger, B., & Rathjen, J. P. (2020). Blurred lines: Integrating emerging technologies to advance plant biosecurity. *Current Opinion in Plant Biology*, 56, 127–134.
- Hueston, W. D., & Singleton, S. (2010). Livestock agroterrorism and the potential public health risk. In J. G. Voeller (Ed.), *Wiley Handbook of Science and Technology for Homeland Security* (pp. 1653–1668). John Wiley and Sons Inc.
- Hugh-Jones, M., & Brown, C. C. (2006). Accidental and intentional animal disease outbreaks: Assessing the risk and preparing an effective response. *Revue Scientifique Et Technique*, 25(1), 21–33.
- Ilbery, B., Maye, D., & Little, R. (2012). Plant disease risk and grower-agronomist perceptions and relationships: An analysis of the UK potato and wheat sectors. *Applied Geography*, 34, 306–315.
- Imperiale, M. J., & Casadevall, A. (2015). A new synthesis for dual use research of concern. *PLoS Medicine*, 12(4). <https://doi.org/10.1371/journal.pmed.1001813>.
- Imperiale, M. J., & Casadevall, A. (2020). Rethinking gain-of-function experiments in the context of the COVID-19 pandemic. *mBio* 11, e01868–20. <https://doi.org/10.1128/mBio.01868-20>
- IPPC. (1997). *International Plant Protection Convention*, FAO, 2011, 18pp.
- IPPC. (2007). *Framework for pest risk analysis. International Standard for Phytosanitary Measures 2*. Produced by the Secretariat of the IPPC. Revised 2019. https://assets.ippc.int/static/media/files/publication/en/2019/05/ISPM_02_2007_En_Framework_PRA_2019-04-30_PostCPM14_InkAm.pdf
- Islam, M. T., Gupta, D. R., Hossain, A., Roy, K. K., He, X., Kabir, M. R., et al. (2020). Wheat blast: A new threat to food security. *Phytopathology Research*, 2, 28. <https://doi.org/10.1186/s42483-020-00067-6>.
- Jones, R. A. C. (2020). Disease pandemics and major epidemics arising from new encounters between indigenous viruses and introduced crops. *Viruses* 12: 1388; 24 pp. <https://doi.org/10.3390/v12121388>
- Jurdak, R., Elfes, A., Kusy, B., Tews, A., Hu, W., Hernandez, E., et al. (2015). Autonomous surveillance for biosecurity. *Trends in Biotechnology*, 33(4), 201–207.
- Just, D. R., Wansink, B., & Turvey, C. G. (2009). Biosecurity, terrorism and food consumption behavior: Using experimental psychology to analyze choices involving fear. *J Ag Res Econ*, 34(1), 91–108.
- Kahn, L. M. (2019). Quantitative framework for coffee leaf rust (*Hemileia vastatrix*), production and futures. *Int. J. Agr. Ext.*, 7(01), 77–87. <https://doi.org/10.33687/ijae.007.01.2744>.
- Kakani, V., Nguyen, V. H., Kumar, B. P., Kim, H., & Pasupuleti, V. R. (2020). A critical review on computer vision and artificial intelligence in food industry. *Journal of Agriculture and Food Research*, 2,.
- Kamenidou, S., Jain, R., Hari, K., Robertson, J. M., & Fletcher, J. (2013). The Microbial Rosetta Stone central agricultural database: An information resource on high-consequence plant pathogens. *Plant Disease*, 97(8), 1097–1102.
- Karlsson, O. K., Hansen, T., Knutsson, R., Löfström, C., Granberg, F., & Berg, M. (2013). Metagenomic detection methods in biopreparedness outbreak scenarios. *Biosecurity and Bioterrorism: Biodefense Strategy, Practice, and Science*, 11(Suppl 1), S146–S157.
- Kelly, A. M. (2005). Veterinary medicine in the 21st century: The challenge of biosecurity. *ILAR Journal*, 46(1), 62–64.
- Keremidis, H., Appel, B., Menrath, A., Tomuzia, K., Normark, M., Roffey, R., & Knutsson, R. (2013). Historical perspective on agroterrorism: Lessons learned from 1945–2012. *Biosecurity and Bioterrorism: Biodefense Strategy, Practice, and Science*, 11(Suppl 1), S17–24.
- Keygene. (2019). First Report of Panama disease in Cavendish bananas caused by Tropical Race 4 in Colombia. *European Nucleotide Archive*. www.ebi.ac.uk/ena/browser/view/PRJNA565135
- Knutsson, R. (2017). Contingency planning and simulation exercises – AniBioThreat training and exercises: conclusions and lessons learned. *Proceedings of the OIE Global Conference on Biological Threat Reduction*, Session 6 – 113–119
- Knutsson, R., Bäverud, V., Elvander, M., Olsson Engvall, E., Eliasson, K., Sternberg Lewerin, S. (2012). Managing and learning from an anthrax outbreak in a Swedish beef cattle herd. In: Hoofar, J. (Ed.). *Case studies in food safety and authenticity: lessons from real-life situations*. Cambridge, UK: Woodhead Publishing Series in Food Science.
- Koblentz, G. D. (2020). Emerging Technologies and the Future of CBRN Terrorism. *The Washington Quarterly*, 43(2), 177–196. <https://doi.org/10.1080/0163660X.2020.1770969>.
- Kraipornsak, P. (2010). The outbreak of avian influenza and chicken consumption in Thailand. *Res Bus Econ*, 2, 1–18.
- Kristensen, E., & Jakobsen, E. B. (2011). Danish dairy farmers' perception of biosecurity. *Preventive Veterinary Medicine*, 115, 1–9.
- Laanen, M., Maes, D., Hendriksen, C., Gelaude, P., De Vliegher, S., Rosseel, Y., & Dewulf, J. (2014). Pig, cattle and poultry farmers with a known interest in research have comparable perspectives on disease prevention and on-farm biosecurity. *Preventive Veterinary Medicine*, 99, 122–129.
- Landa, B. B., Castillo, A. I., Giampetruzzi, A., Kahn, A., Román-Écija, M., Velasco-Amo, M. P., et al. (2020). Emergence of a plant pathogen in Europe associated with multiple intercontinental introductions. *Applied and Environment Microbiology*, 86, e01521-e1619. <https://doi.org/10.1128/AEM.01521-19>.
- Latxague, E., Sache, I., Pinon, J., Andrivon, D., Barbier, M., & Suffert, F. (2007). A methodology for assessing the risk posed by the deliberate and harmful use of plant pathogens in Europe. *EPPO Bulletin*, 37(2), 427–435.
- Léger, A., De Nardi, M., Simons, R., Adkin, A., Ru, G., Estrada-Peña, A., & Stärk, K. D. C. (2017). Assessment of biosecurity and control measures to prevent incursion and to limit spread of emerging transboundary animal diseases in Europe: An expert survey. *Vaccine*, 35, 5956–5966. <https://doi.org/10.1016/j.vaccine.2017.07.034>.
- Lewis, G., Jordan, J. L., Relman, D. A., Koblentz, G. D., Leung, J., Dafoe, A., et al. (2020). The biosecurity benefits of genetic engineering. *Nature Communications*, 11, 6294. <https://doi.org/10.1038/s41467-020-19149-2.4pp>.
- Lin, L., Rivera, C., Abrahamsson, M., & Tehler, H. (2017). Communicating Risk in Disaster Risk Management Systems – Experimental Evidence of the Perceived Usefulness of Risk Descriptions. *Journal of Risk Research*, 20(12), 1534–1553. <https://doi.org/10.1080/13669877.2016.1179212>.
- Linacre, N. A., Koo, B., Rosegrant, M. W., Msangi, S., Falck-Zepeda, J., Gaskell, J., Komen, J., Cohen, M. J., & Birner, R. (2005). *Security Analysis for Agroterrorism: Applying the Threat, Vulnerability, Consequence Framework to Developing Countries*. International Food Policy Research Institute (IFPRI). EPT Discussion paper 138, Washington DC, USA, 50 pp.

- Lindberg, A., & Melin, L. (2016). Nätverk stärker beredskap för farliga smittämnen. *Svavet*, 1, 6 (in Swedish).
- Luers, A. L., Lobella, D. B., Sklar, L. S., Addams, C. L., & Matson, P. A. (2003). A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico. *Global Environmental Change*, 13, 255–267. [https://doi.org/10.1016/S0959-3780\(03\)00054-2](https://doi.org/10.1016/S0959-3780(03)00054-2).
- MacDonald, J., Allen, C., Gadoury, D., Jacobi, W., Kelemu, S., Moyer, J., Murray, T., Ong, K., Pearson, C., Sherwood, J., & Vidaver, A. (2009). Education in Plant Pathology Present Status and Future Challenges. *Papers in Plant Pathology* 322. <http://digitalcommons.unl.edu/plantpathpapers/322>
- Mackelprang, R., & Friedman, D. C. (2021). Agricultural crop security: Exploring US federal readiness and response capabilities. *Health Security*, 19(5), 1–10. <https://doi.org/10.1089/hs.2020.0153>.
- Mackereth, G. F., & Stone, M. A. B. (2006). Veterinary intelligence in response to a foot-and-mouth disease hoax on Waiheke Island, New Zealand. *Proceedings of the 11th International Symposium on Veterinary Epidemiology and Economics*. www.sciquest.org.nz/node/63926
- Madden, L. V., Hughes, G., & van den Bosch, F. (2007). *The study of plant disease epidemics*. APS Press.
- Madden, L. V., & Wheelis, M. (2003). The threat of plant pathogens as weapons against US crops. *Ann. Rev. Phytopathol.*, 41, 155–176.
- Martelli, G. P., Boscia, D., Porcelli, F., & Saponari, M. (2016). The olive quick decline syndrome in south-east Italy: A threatening phytosanitary emergency. *European Journal of Plant Pathology*, 144, 235–243. <https://doi.org/10.1007/s10658-015-0784-7>.
- Maryani, N., Lombard, L., Poerba, Y. S., Subandiyah, S., Crous, P. W., & Kema, G. H. J. (2019). Phylogeny and genetic diversity of the banana Fusarium wilt pathogen *Fusarium oxysporum* f. sp. *cubense* in the Indonesian centre of origin. *Studies in Mycology*, 92, 155–194. <https://doi.org/10.1016/j.simyco.2018.06.003>.
- McDonald, B. A., & Stukenbrock, E. H. (2016). Rapid emergence of pathogens in agro-ecosystems: Global threats to agricultural sustainability and food security. *Phil. Trans. r. Soc. B*, 371, 20160026. <https://doi.org/10.1098/rstb.2016.0026>.
- McDonald, B. L. (2013). Ensuring food security. Meeting challenges from malnutrition, food safety, and global environmental change. Ch 13 in: Floyd, R., & Matthew, R. (eds.), *Environmental Security: Approaches and Issues*, Taylor & Francis Group, London. 234–247.
- Meadows, A. J., Mundt, C. C., Keeling, M. J., & Tildesley, M. J. (2018). Disentangling the influence of livestock vs. farm density on livestock disease epidemics. *Ecosphere* 9(7): e02294. 13 pp. <https://doi.org/10.1002/ecs2.2294>
- Menrath, A., Tomazia, K., Frentzel, H., Braeunig, J., & Appel, B. (2014). Survey of systems for comparative ranking of agents that pose a bioterroristic threat. *Zoonoses and Public Health*, 61, 157–166.
- Meslin, F.-X. (1997). Global Aspects of Emerging and Potential Zoonoses: A WHO Perspective. *Emerging Infectious Diseases*, 3(2), 223–228.
- 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, 780–786.
- Minato, N., Sok, S., Chen, S., Delaquis, E., Phirun, I., Le, V. X., et al. (2019). Surveillance for Sri Lankan cassava mosaic virus (SLCMV) in Cambodia and Vietnam one year after its initial detection in a single plantation in 2015. *PLoS One*, 14, <https://doi.org/10.1371/journal.pone.0212780>.
- Mohtadi, H., & Murshid, A. (2006). *A global chronology of incidents of chemical, biological, radioactive and nuclear attacks: 1950–2005*. University of Wisconsin, Milwaukee. <https://people.uwm.edu/mohtadi/files/2016/07/A-Global-Chronology-of-Incidents-of-Chemical-Biological-and-Radionuclear-Attacks.docx>
- Mumford, J. D., Leach, A. W., Holt, J., Suffert, F., Sache, I., Moignot, B., & Hamilton, R. A. (2017). Integrating crop bioterrorism hazards into pest risk assessment tools. In M. L. Gullino, J. P. Stack, J. Fletcher, & J. D. Mumford (Eds.), *Practical Tools for Plant and Food Biosecurity: Results from a European Network of Excellence* (pp. 121–142). Springer International Publishing, Cham.
- Månsson, P., Abrahamsson, M., & Tehler, H. (2019). Aggregated risk: An experimental study on combining different ways of presenting risk information. *Journal of Risk Research*, 22(4), 497–512. <https://doi.org/10.1080/13669877.2017.1391315>.
- Mårtensson, P. Å., Hedström, L., Sundelius, B., Skiby, J. E., Elbers, A., & Knutsson, R. (2013). Actionable knowledge and strategic, decision making for bio- and agroterrorism threats: Building a collaborative early warning culture. *Biosecurity and Bioterrorism: Biodefense Strategy, Practice, and Science*, 11(Suppl), S46–S54.
- NAO (National Audit Office). (2002). *The 2001 outbreak of Foot and Mouth Disease*. Report by the comptroller and auditor general. HC939 Session 2001–2002. www.nao.org.uk/wp-content/uploads/2002/06/0102939.pdf
- Niemi, J. (2012). The significance of agricultural input trade in global food production. *Bulletin of the Finnish Agricultural Society*, 28, 1–5.
- Nöremark, M., & Sternberg-Lewerin, S. (2014). On-farm biosecurity as perceived by professionals visiting Swedish farms. *Acta Veterinaria Scandinavica*, 56, 28.
- Oerke, E. C. (2006). Crop losses to pests. *Journal of Agricultural Science*, 144, 31–43.
- O'Hara, P. (2006). The illegal introduction of rabbit haemorrhagic disease virus in New Zealand. *Revue Scientifique Et Technique*, 25(1), 119–123.
- OIE. (2019). Import risk analysis. Ch 2.1 in: *OIE - Terrestrial Animal Health Code - 28/06/2019*. 5 pp. www.oie.int/fileadmin/Home/eng/Health_standards/tahc/current/chapitre_import_risk_analysis.pdf
- OIE (World Organisation for Animal Health). (2021). *OIE-Listed diseases, infections and infestations in force in 2020*. www.oie.int/en/animal-health-in-the-world/oie-listed-diseases-2021/
- Olofsson, E., Nöremark, M., & Sternberg Lewerin, S. (2014). Patterns of between-farm contacts via professionals in Sweden. *Acta Veterinaria Scandinavica*, 56, 70.
- Ordóñez, N., Seidl, M. F., Waalwijk, C., Drenth, A., Kilian, A., Thomma, B. P. H. J., et al. (2015). Worse Comes to Worst: Bananas and Panama Disease—When Plant and Pathogen Clones Meet. *PLOS Pathogens*. <https://doi.org/10.1371/journal.ppat.1005197>. November 19, 2015, 7pp.
- Parnell, S., van den Bosch, F., Gottwald, T., & Gilligan, C. A. (2017). Surveillance to Inform Control of Emerging Plant Diseases: An Epidemiological Perspective. *Ann. Rev. Phytopathol.*, 55, 591–610.
- Paterson, R. R. M. (2006). Fungi and fungal toxins as weapons. *Mycological Research*, 110(9), 1003–1010.
- Pautasso, M., Petter, F., Rortais, A., & Roy, A. S. (2015). Emerging risks to plant health: A European perspective. *CAB Reviews*, 10(021), 1–16. <https://doi.org/10.1079/PAVSNNR201510021>.
- Peck, D. F. (2005). Foot and mouth outbreak: Lessons for mental health services. *Advances in Psychiatric Treatment*, 11, 270–276.
- Pettersson, L., & Widell, L. (2010). Den produktionsekonomiska betydelsen av kontrollprogram för Salmonella hos nötkreatur. Jordbruksverkets rapport 2010:2. SJV, Jönköping, Sweden. (in Swedish).
- Pilch, R., Pomper, M., Luster, J., & Lentzos, F. (2020). A guide to investigating outbreak origins: Nature versus the laboratory. *CNS*

- Occasional paper #49*, October 2020. Middlebury Institute of International Studies at Monterey. 32 pp.
- Renault, V., Damiaans, B., Humblert, M.-F., Ruiz, S. J., Bocanegra, I. G., Brennan, M. L., et al. (2020). Cattle farmers' perception of biosecurity measures and the main predictors of behaviour change: The first European-wide pilot study. *Transboundary and Emerging Diseases*, 00, 1–15. <https://doi.org/10.1111/tbed.13935>.
- Richardson, J., Lockhart, C., Pongolini, S., Karesh, W. B., Baylis, M., Goldberg, T., Slingenbergh, J., Gale, P., Venturini, T., Catchpole, M., de Balogh, K., Pautasso, M., Broglia, A., Berthe, F., Schans, J., & Poppy, G. (2016). Drivers for emerging issues in animal and plant health. *EFSA Journal* 14(S1): s0512. 11 pp. <https://doi.org/10.2903/j.efsa.2016.s0512>
- Robb, P. (2017). Considering vulnerabilities, threats and gaps in plant food biosecurity. In: Gullino, M.L., Stack, J.P., Fletcher, J., & Mumford, J.D. (Eds.). *Practical Tools for Plant and Food Biosecurity: Results from a European Network of Excellence*, Springer International Publishing, Cham, Switzerland; 2017, pp 1–30.
- Royal Society of Edinburgh. (2002). Inquiry into Foot and Mouth Disease in Scotland, July 2002. www.rse.org.uk/wp-content/uploads/2016/09/Foot-and-Mouth-Disease.pdf
- Rydmark, J., Kuylenstierna, J., & Tehler, H. (2020). Communicating uncertainty in risk descriptions: The consequences of presenting imprecise probabilities in time critical decision-making situations. *Journal of Risk Research*, 24, 629–644. <https://doi.org/10.1080/13669877.2020.1801807>.
- Salman, M., Silano, V., Heim, D., & Kreysa, J. (2012). Geographical BSE risk assessment and its impact on disease detection and dissemination. *Preventive Veterinary Medicine*, 105(4), 255–264. <https://doi.org/10.1016/j.prevetmed.2012.01.006>.
- Savary, S., Willocquet, L., Pethybridge, S. J., Esker, P., McRoberts, N., & Nelson, A. (2019). The global burden of pathogens and pests on major food crops. *Nature Ecology & Evolution*, 430(3), 430–439.
- Schaad, N. W., Abrams, J., Madden, L. V., Frederick, R. D., Luster, D. G., Damsteegt, V. D., & Vidaver, A. K. (2006). An assessment model for rating high-threat crop pathogens. *Phytopath.*, 96(6), 616–621.
- Schneider, K., van der Werf, W., Cendoya, M., Mouritsa, M., Navas-Cortés, J. A., Vicent, A., & Lansink, A. O. (2020). Impact of *Xylella fastidiosa* subspecies *pauca* in European olives. *PNAS* April 28, 2020, 117(17), 9250–9259.
- Selgelid, M. J. (2009). Governance of dual-use research: An ethical dilemma. *Bull WHO*, 87, 729–723.
- Selgelid, M. J. (2016). Gain-of-Function Research: Ethical Analysis. *Science and Engineering Ethics*, 22, 923–964. <https://doi.org/10.1007/s11948-016-9810-1>.
- Shaw, M. W., & Osborne, T. M. (2011). Geographic distribution of plant pathogens in response to climate change. *Plant Pathology*, 60, 31–43. <https://doi.org/10.1111/j.1365-3059.2010.02407.x>.
- Siriwan, W., Jimenez, J., Hemniam, N., Saokham, K., Lopez-Alvarez, D., Leiva, A. M., Martinez, A., & Mwanzia, L., Lopez-Lavalle, L. A. B., & Cuellar, W. J. (2020). Surveillance and diagnostics of the emergent Sri Lankan cassava mosaic virus (Fam. *Geminiviridae*) in Southeast Asia. *Virus Research* 285: 197959, 5 pp.
- Spackman, E. (2020). A Brief Introduction to Avian Influenza Virus. In: Spackman, E. (Ed.) *Animal Influenza Virus. Methods in Molecular Biology* 2123: 83–92. Humana, New York, NY. https://doi.org/10.1007/978-1-0716-0346-8_7
- Spink, J., & Moyer, D. C. (2011). Defining the public health threat to food fraud. *Journal of Food Science*, 76, 157–163.
- Stack, J. P., Bostock, R. M., Hammerschmidt, R., Jones, J. B., & Luke, E. (2014). The National Plant Diagnostic Network: Partnering to Protect Plant Systems. *Plant Disease*, 98(6), 708–715.
- Stokstad, E. (2017). Deadly virus threatens European pig and boar. *Science* 358(6370): 1516–1517. 22 Dec 2017. <https://doi.org/10.1126/science.358.6370.1516>
- Suffert, F., Latxague, E., & Sache, I. (2009). Plant pathogens as agroterrorist weapons: Assessment of the threat for European agriculture and forestry. *Food Security*, 1, 221–232.
- Suffert, F. (2017). Characterization of the threat resulting from plant pathogen use as anti-crop bioweapons: An EU perspective on agroterrorism. In M. L. Gullino, J. P. Stack, J. Fletcher, & J. D. Mumford (Eds.), *Practical Tools for Plant and Food Biosecurity: Results from a European Network of Excellence* (pp. 31–60). Springer International Publishing, Cham.
- Sundström, J. F., Albiñ, A., Boqvist, S., Ljungvall, K., Marstorp, H., Martiin, C., et al. (2014). Future threats to agricultural food production posed by environmental degradation, climate change, and animal and plant diseases – a risk analysis in three economic and climate settings. *Food Security*, 6, 201–215. <https://doi.org/10.1007/s12571-014-0331-y>.
- SVA. (2021). Coronakommissionen om SVA. (in Swedish) <https://www.sva.se/aktuellt/nyheter/coronakommissionen-om-sva/>
- Tembo, B., Mulenga, R.M., Sichilima, S., M'siska, K. K., Mwale, M., Chikoti, P. C., Singh, P. K., He, X., Pedley, K. F., Peterson, G. L., Singh, R. P., Braun, H. J. (2020). Detection and characterization of fungus (*Magnaporthe oryzae pathotype Triticum*) causing wheat blast disease on rain-fed grown wheat (*Triticum aestivum* L.) in Zambia. *PLoS One* 15(9), e0238724. <https://doi.org/10.1371/journal.pone.0238724>
- Thelau, J., Lindberg, A., Thisted Lambertz, S., Byström, M., Forsman, M., Lindmark, H., et al. (2017). Network experiences from a cross-sector biosafety level-3 laboratory collaboration: A Swedish forum for biopreparedness diagnostics. *Health Secur*, 15(4), 384–391.
- Thompson, D., Muriel, P., Russel, D., Osborne, P., Bromley, A., Rowland, M., et al. (2002). Economic costs of the foot and mouth disease outbreak in the United Kingdom in 2001. *Revue Scientifique Et Technique*, 21(3), 675–687.
- Tozer, P., & Marsh, T. L. (2012). Domestic and trade impacts of foot-and-mouth disease on the Australian beef industry. *The Australian Journal of Agricultural and Resource Economics*, 56, 385–404. <https://doi.org/10.1111/j.1467-8489.2012.00586.x>.
- Treadwell, T. A., Koo, D., Kukur, K., & Khan, A. S. (2003). Epidemiologic clues to bioterrorism. *Public Health Reports*, 118(2), 92–98.
- Turner, B. L., Kaspersen, R. R., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., et al. (2003). A framework for vulnerability analysis in sustainability science. *PNAS*, 100(14), 8074–8079. <https://doi.org/10.1073/pnas.1231335100>.
- Turvey, C. G., Onyango, B., Cuite, C., & Hallman, W. K. (2010). Risk, fear, bird flu and terrorists: A study of risk perceptions and economics. *J Soc Eco*, 39(1), 1–10.
- Ungerer, C., & Rogers, D. (2006). The threat of agroterrorism to Australia: A preliminary assessment. *Stud Confl Terror*, 29(2), 147–163.
- Utne, I. B., Hokstad, P., Kjølle, G., Vatn, J., Tøndel, I. A., Bertelsen, D., Fridheim, H. & Røstum, J. (2008). *Risk and vulnerability analysis of critical infrastructures – the DECRIS approach*. In: SAMRISK conference, Oslo. www.sintef.no/project/SAMRISK/DECRIS/Documents/DECRIS_paper_SAMRISK_final%20080808.pdf
- Valceschini, E. (2006). Poultry meat trends and consumer attitudes. In: *Proceedings of the XII European Poultry Conference*, Verona, Italy, 10–14 September 2006, paper no. 359, 10 pp.
- Valles, E. G., & Bernacchi, S. (2014). Do Latin American scientific journals follow dual-use review policies? *Biosecurity and Bioterrorism: Biodefense Strategy, Practice, and Science*, 12, 94–105.
- Van der Fels-Klerx, H. J., Van Asselt, E. D., Raley, M., Poulsen, M., Korsgaard, H., Bredsdorff, L., et al. (2018). Critical review of methods for risk ranking of food-related hazards, based on risks for human health. *Critical Reviews in Food Science and Nutrition*, 58(2), 178–193. <https://doi.org/10.1080/10408398.2016.1141165>.
- van Tuyl, M. (2013). Dealing with future risks in the Netherlands. *Biosecurity and Bioterrorism: Biodefense Strategy, Practice,*

and Science, 11(Supplement), 1. <https://doi.org/10.1089/bsp.2012.0075>.

- Vasconcelos Gioia, G., Lamielle G., Aguanno, R., ElMasry, I., Mouillé, B., De Battisti, C., Angot, A., Ewann, F., Sivignon, A., Donachie, D., Rozov, O., Bonbon, E., Poudevigne, F., VonDobschuetz, S., Plée, L., Kalpravidh, W., & Sumption, K. (2021). Informing resilience building: FAO's Surveillance Evaluation Tool (SET) Biothreat Detection Module will help assess national capacities to detect agroterrorism and agro-crime. *One Health Outlook* 3:14. 13 pp. <https://doi.org/10.1186/s42522-021-00045-8>
- Waage, J. K., & Mumford, J. D. (2008). Agricultural biosecurity. *Philosophical Transactions of the Royal Society b: Biological Sciences*, 363, 863–876.
- Webster, R. G., & Walker, E. J. (2003) Influenza: The world is teetering on the edge of a pandemic that could kill a large fraction of the human population. *American Scientist* 91(2), 122–129. www.jstor.org/stable/27858180
- Wheelis, M., Casagrande, R., & Madden, L. V. (2002). Biological attack on agriculture: Low-tech, high-impact bioterrorism. *BioScience*, 52(7), 569–576.
- WHO (World Health Organization), FAO, & OIE. (2004). *Report of WHO/FAO/OIE joint consultation on emerging zoonotic diseases*. May 3–5, 2004, Geneva, Switzerland. WHO/CDS/CPE/ZFK/2004.9. 72 pp. https://apps.who.int/iris/bitstream/handle/10665/68899/WHO_CDS_CPE_ZFK_2004.9.pdf
- WHO (World Health Organization). (2010). *Responsible life sciences research for global health security: A guidance document*. WHO Press; Geneva.
- Wilkinson, K., Grant, W. P., Green, L. E., Hunter, S., Jeger, M. J., Lowe, P., et al. (2011). Infectious diseases of animals and plants: An interdisciplinary approach. *Phil Trans R Soc B*, 366, 1933–1942.
- Wilson, T. M., Logan-Henfrey, L., Weller, R., & Kellman, B. (2000). Agroterrorism, biological crimes and biological warfare targeting animal agriculture. In C. Brown & C. Bolin (Eds.), *Emerging Diseases of Animals* (pp. 23–57). ASM Press.
- Winehav, M., & Nevhage, B. (Eds.). (2011). [FOI:s modell för risk- och sårbarhetsanalys (FORSA)]. Report FOI-R—3288—SE, 140 pp.
- World Bank. (2019). Rural population (% of total population). <https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS> Accessed February 21, 2021.
- World Bank. (2021). Agriculture, forestry, and fishing, value added (% of GDP). <https://data.worldbank.org/indicator/NV.AGR.TOTL.ZS>
- Wright, D., MacLeod, B., Hammond, N., & Longnecker, N. (2016). Can grain growers and agronomists identify common leaf diseases and biosecurity threats in grain crops? An Australian example. *Crop Protection*, 89, 78–88.
- Wu, J. T., Leung, K., Lam, T. T. Y., Ni, M. Y., Wong, C. K. H., Peiris, J. S. M., & Leung, G. M. (2021). Nowcasting epidemics of novel pathogens: lessons from COVID-19. *Nature Medicine* 388: 388–395, 27 March 2021. <https://doi.org/10.1038/s41591-021-01278-w>
- Yudelman, M., Ratta, A., & Nygaard, D. (1998). Pest Management and Food Production. Looking to the Future. In *Food, Agriculture, and the Environment Discussion Paper 25*. International Food Policy Research Institute, Washington, USA, 59.
- Zadoks, J. C., & Schein, R. D. (1979). *Epidemiology and plant disease management*. Oxford University Press.

Zhan, J., Thrall, P. H., Papaix, J., Xie, L., & Burdon, J. J. (2015). Playing on a Pathogen's Weakness: Using Evolution to Guide Sustainable Plant Disease Control Strategies. *Ann. Rev. Phytopathol.*, 53, 19–43.



Annika Djurle had her undergraduate and PhD education in agronomy and plant pathology respectively, at the Swedish University of Agricultural Sciences in Uppsala. She is now retired from positions as senior lecturer and researcher in plant pathology with specialization in plant disease epidemiology. Her main research area has been fungal diseases in agricultural crops, addressing subjects such as integrated disease management, yield loss, estimation of disease risk, evaluation of disease resistance and pathogen population structure. She has several years of teaching

experience at BSc, MSc, and PhD levels.



Beth Young received her Doctor of Veterinary Medicine and Doctor of Veterinary Science degrees from the University of Guelph in Canada. Her research has focused on swine reproduction and the spread and control of viral diseases in pig populations. She is currently working as an epidemiologist at the Swedish National Veterinary Institute in Uppsala where she coordinates national animal disease surveillance programs and acts as an advisor during investigations of epizootic and zoonotic disease suspicions and outbreaks.



Anna Berlin is associate professor in biology with specialization in plant pathology. She received her undergraduate and PhD education at the Swedish University of Agricultural Sciences (SLU) in Uppsala. Since her PhD (2012) Anna has worked as a researcher in plant pathology, with a focus on plant disease epidemiology in future agricultural and climatic scenarios by studying population dynamics of pathogens to understand the occurrence, distribution, management and risk assessment of plant diseases. She is currently

the director of studies for the BSc and MSc education in agricultural crop and soil management at SLU.



Ivar Vågsholm is professor in food safety at SLU since 2009 and since 2015 head of the department of Biomedicine and Veterinary Public Health. He graduated as a veterinarian in 1984 and obtained his PhD from University of California 1989. He has worked with European Union questions relating to animal health and food safety the last 30 years. Key research areas include veterinary public health including epidemiology and risk analysis with a focus on revision of meat inspection, food safety legislation, organizing

food control systems and control of TSE. Currently the main interests are circular food production systems and novel foods and feeds, in particular avoiding cycles of nutrients becoming cycles of infectious agents.



Anne-Lie Blomström obtained her PhD in 2010 and is now an associate professor in molecular virology at the department of Biomedicine and Veterinary Public Health at the Swedish University of Agricultural Sciences. Apart from research she is also involved in teaching at both undergraduate and graduate levels. The main research areas include the use of high throughput sequencing and bioinformatics for virus discovery

as a mean to both understand the aetiology of diseases and the circulation of viruses in our environment. She has a specific focus on vector-borne viruses and also investigates their interactions with their host/vector.



Jim Nygren had his undergraduate education at Uppsala University and his PhD education at the Swedish University of Agricultural Sciences in Uppsala. His main research area has been plant breeding for disease resistance in wheat.



Anders Kvarnheden is since 2013 professor in plant virology at the Swedish University of Agricultural Sciences (SLU) and he is presently also visiting professor at the Estonian University of Life Sciences. He obtained his PhD from Uppsala University in physiological botany in 1994 working on molecular genetics and developmental biology of plants. From 1998, his research has focused on

the molecular epidemiology of plant-infecting viruses. Key questions are to understand virus diversity and how it is formed as well as how virus diseases of crops can be managed. He is active in education with teaching in multiple courses at different levels and the management of master studies in plant biology.