Chapter 6
Decreases in Crop Production by Non-native Weeds, Pests, and Pathogens

Guillaume Fried, Bruno Chauvel, Philippe Reynaud, and Ivan Sache

Abstract The worldwide trade of agricultural products and high levels of disturbance and fertilisation make arable lands particularly vulnerable to biological invasions. Clearing for the development of arable land has been an unprecedented event that created a new and more homogeneous habitat which allowed many species to spread to become (sub)cosmopolitan weeds, pests, and pathogens. Through competition for light, water, and nutrients (weeds), or destruction of plant tissue (pests and pathogens), harmful organisms can potentially reduce crop yield by 10–40 % on average. Historically, some non-native species produced spectacular invasions and caused incalculable damage by annihilating crop production at large scales: for example, potato late blight, *Phytophthora infestans*, which was one of the factors causing the Irish Potato Famine, and the American vine phylloxera, *Daktulosphaira vitifoliae*, which devastated vineyards across the whole of Europe. Nowadays, it is estimated that non-native weeds, pests, and pathogens cause as much as US$248 billion in annual losses to world agriculture, making this the sector most affected by the introduction of non-native species. The use of pesticides has long protected crop yield satisfactorily. However, because of the undesirable side effects that may be associated with pesticide use (e.g., development of resistant biotypes and water pollution), more integrated approaches to combat invasive species are needed, including prevention (phytosanitary control) and cropping systems with higher potential for ecological regulation.

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6.1 Introduction

Since the development of agriculture during the Neolithic Period, a large number of crop species have been cultivated on arable lands to produce food or fibre. This new man-made environment has expanded continuously to amount to 1386 million ha, that is, 10 % of the world's land area. Cropland is particularly prone to biological invasions that proceed through the different steps of introduction, establishment, and spread. The introduction of crop species into new regions has concomitantly promoted the accidental introductions of many weeds (plants interfering with crops), pests, and pathogens strongly associated with the crops in their native range. In contrast to other unintentional pathways of introduction (e.g., soil or commodities, such as wool or wood), unintentional introduction of non-native weeds, pests, and pathogens with crop seeds or on ornamental plants may have greater success because they are likely to have been introduced in a suitable climate similar to that of their region of origin.

In many aspects, arable lands can be considered as very simplified ecosystems with few bottom-up and top-down regulations (Altieri 1999). The environment is strongly modified and controlled to optimize the growth of cultivated plants. Regular soil tillage, fertilisation, and irrigation lead to a high level of disturbances and soil resource availability. This situation also translates into a large amount of nutrient-rich biomass that makes the crop a very attractive resource for primary consumers, compared to the vegetation in the surrounding areas. Although arable fields constitute a mosaic of different crop species at the regional scale, the few dominant varieties used for each crop species result in a strong genetic uniformity over large areas. For example, in the USA, 60–70 % of the total common bean area is planted with only two or three varieties. Thus, management practices favour habitat characteristics that enhance biological invasions: low species richness, frequent disturbances, and high resource availability (Booth et al. 2003).

Considering both the extent and economic importance of biological invasions in crop fields, this chapter first reviews the patterns of invasion of non-native weeds, pests, and pathogens in arable lands with regard to pathways of introduction and biological traits, and then describes the causes and consequences of their impacts on crop production.

6.2 Patterns of Invasion in Arable Crops

6.2.1 Proportion of Non-native Species in Arable Crops

The inventories of non-native species available throughout the world show that arable lands often harbor the major part of non-native species established in a given area. In Europe, about 50 % of all non-native plants, and almost 30 % of all non-native arthropods, can be found in agricultural and horticultural lands (DAISIE 2009). In the USA, 73 %, 65 %, and 40 % of the weeds, pathogens, and insect pests of crops are non-native (Pimentel et al. 2005). These are very high proportions, considering that for the whole USA non-native insects and non-native plants constitute only 2 % and 18 % of the entire insect fauna or flora, respectively. The figures are lower for pathogens. In Europe, some 20 fungal pathogens of economic significance have been established since 1800 (Desprez-Loustau et al. 2010). In Great Britain, 30 species have been recorded on arable crops among the 235 species of plant pathogens of quite recent introduction (1970–2004) (Jones and Baker 2007).

6.2.2 Main Pathways and Biogeographical Origins

Most non-native weeds, pests, and pathogens have been introduced unintentionally as contaminants of agricultural or horticultural commodities, including seeds of crops for sowing (mostly for weeds), and other commodities, such as plants for planting or cut flowers (for pests and pathogens). These introductions started long ago, during the Neolithic Period (~6000 BC), with the spread from the Near East to Western Europe of weeds such as *Agrostemma githago* or *Cyanus segetum*, or insect fauna of stored grain such as the flightless weevil, *Sitophilus granarius*, or the beetle, *Tribolium confusum*.

There is often no agreement regarding the exact area of origin of weeds, pests, and pathogens, especially for "human commensal" species that achieved a cosmopolitan distribution long ago. It is often believed that their area of origin corresponds to the centre of origin of the crop with which they are associated. In Europe, the natural distribution range of many anciently introduced weed and pest species probably coincided with that of the wild progenitors of wheat and barley in the Near and Middle East and then travelled westwards with early agriculturists. Similarly, there is increased evidence on the emergence of pathogens within the crop diversification areas and their subsequent spread in association with crop domestication, human migrations, and the development of agriculture (Banke and McDonald 2005).

More recently, neophytic weeds (i.e., introduced after 1500 AD), such as species of *Amaranthus* or *Panicum*, were introduced in Europe from America with contaminated seeds of crops such as maize or soybean. In France, the second and the third most important area of origin of neophytic weeds is North America (20 %) and South America (16 %), just after the Mediterranean Basin (22 %). Similarly, a large proportion of the introductions of non-native weeds and insects in the USA were associated early with European migration and later by international trade with other continents. In Great Britain, the ten recently introduced plant pathogens of known origin were imported from the three countries of continental Europe (France, Netherlands, and Spain) with the largest crop production or export (Jones and Baker 2007). This scenario illustrates how the donor regions tend to reflect trends in the major trade flow of agricultural products.

6.2.3 General Biological Traits

Although it is difficult to find a common suite of traits shared by all or even most non-native invasive species in natural and seminatural habitats, the more homogeneous and stringent conditions prevailing in arable lands permits a broad picture of invasive species that succeed in such disturbed environments. They generally belong to the *r*-strategist species category, with traits such as high fecundity, short lifespan, high growth rate, and plasticity.

Based on the list of noxious weeds of the Weed Science Society of America, Kuester et al. (2014) showed that weedy plants (both native and non-native) are more likely to be annuals, exhibit a fast growth rate, and have high fruit abundance, high seedling vigour, and rapid vegetative spread. This list covers many traits of the ideal weeds defined by Baker (1965), but their relative importance for weed success can vary according to local cropping systems. Indeed, successful weeds can differ according to the crop types considered, based on the synchronisation of their life cycle (especially timing of emergence) with that of the crop or on their tolerance to the spectrum of herbicides used in the crop (Fried et al. 2009).

Certain traits predispose arthropods to establish successfully, such as their small size, good powers of flight, high rate of reproduction (many species are also parthenogenetic), ability to reach high numbers, cryptic behavior, egg deposition on or inside plant tissue or in soil, and propensity to secrete themselves in tight spaces (Roques et al. 2010). The likelihood of establishment also increases when the invader arrives with a large founding population and is preadapted to the new environment.

Pathogens, especially fungi, have a strong invasive potential because of their diversity of dispersal modes, their short generation time, and high fertility; most species exhibit phenotypic plasticity and evolutionary potential, which allows them to thrive in a wide range of environments (Desprez-Loustau et al. 2007).

6.3 Impact of Non-native Species on Crop Production

Decreases in crop production, or more specifically, yield losses, are calculated as the difference between the attainable and the actual yield (Fig. 6.1). Crop losses occur because the physiology of the growing crop is negatively affected by weeds, pests, and pathogens. Some non-native species have been involved in spectacular invasions that damaged crops over large areas in a few years and strongly affected human populations in the nineteenth century. The pathogen causing potato late blight, *Phytophthora infestans*, was one of the factors responsible for the Irish Potato Famine that caused more than 1 million persons to starve to death and forced another million to emigrate (Fig. 6.2). The struggle against the American vine phylloxera, *Daktulosphaira vitifoliae*, that destroyed most of the European vineyards in the late nineteenth century was the first example of international cooperation against a pest. This effort constituted the first steps that led to the creation of the IPPC (International Plant Protection Convention) that was established to facilitate international cooperation in controlling plant pests and to prevent their international spread (van der Graaff and Khoury 2010).

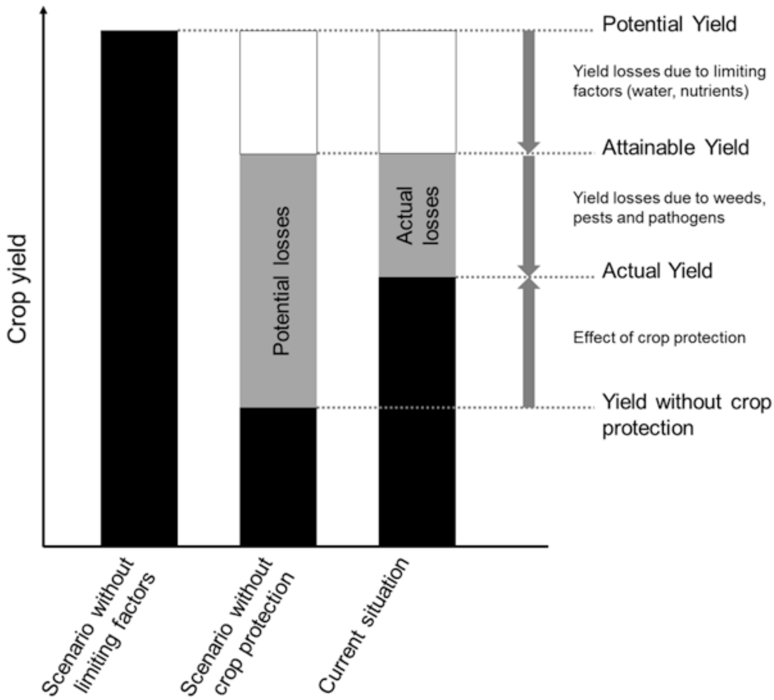

Fig. 6.1 The different yield levels and abiotic and biotic factors causing crop losses (From Oerke 2006 and other sources)

Fig. 6.2 Assessment of field resistance to potato late blight caused by *Phytophthora infestans*, in an array of potato cultivars left without fungicide protection. Resistant cultivars were hardly impacted by the disease while susceptible cultivars were totally defoliated (Photograph by D. Andrivon. © INRA Ploudaniel)

6.3.1 Mechanisms Underlying the Effects of Non-native Species on Crops

Damage mechanisms inducing crop losses can be classified into different categories based on the timing (i.e., before or after harvest of the crop), and on the direct and indirect nature of the effects on crop plants (see Table 6.1). Moreover, damages can result in a reduction of the quantity or the quality of the harvested crop.

6.3.1.1 Weeds

There are three primary mechanisms of interference between weeds and crops: competition, allelopathy, and parasitism. Most weeds have an effect on crop yield through resource competition for available light, water, and nutrients (Zimdahl 2004; Table 6.1). Another mechanism, which may have more impact in the case of newly introduced non-native weeds, is *allelopathy* (Table 6.2), that is, the release of chemical compounds that might have harmful effects on the growth of the crop

Table 6.1 Crop damage (or injury) mechanisms based on various sources

Timing of damages	Type of damages[a]	Damage mechanisms	Effect	Examples of harmful organisms
Pre-harvest	Direct	Stand (crop density) reducers	Weaken seeds or seedlings before or after they germinate; weaken the stem and cause the crop plant to fall over	Damping-off pathogens, arthropods, including Lepidoptera (cutworms), Coleoptera (rootworms) and Diptera
		Fruit/seed-feeders	Damage parts of plants that are harvested	Chewing and sucking arthropods, birds
	Indirect	Photosynthetic rate reducers	Reduce the rate of carbon uptake	Fungi, bacteria, viruses, gall making and leaf-mining arthropods
		Leaf senescence accelerators	Increase leaf senescence, causes defoliation	Pathogens, arthropods sucking cell contents and leaf-mining arthropods
		Tissue consumers	Reduce tissue biomass	Chewing arthropods, necrotrophic pathogens
		Turgor reducers	Disrupt xylem and phloem transport	Vascular, wilt pathogens, insects
		Assimilate sappers	Remove soluble assimilates from host	Nematodes, pathogens, phloem- or xylem-sucking arthropods, parasitic weeds
		Light stealers	Reduce the intercepted radiation	Non-parasitic weeds, leafspot pathogens
		Nutrient and water stealers (competition)	Reduce the nutrient & water uptake	Non-parasitic weeds
		Growth inhibitors/ regulators	Prevent seedling emergence or regulates plant growth	Allelopathic weeds
Post-harvest	Direct	Fruit/seed-feeders	Reduce the number and biomass of marketable products	Stored grain arthropods, rodents, birds
	Indirect	Contamination of fruits or grains	Damage harvested organs	Fungi
		Market price downgrading	Decrease technological or visual quality	Fungi, bacteria, weeds, arthropods
		Food poisoning	Release toxins	Fungi, bacteria, poisonous weeds

[a]*Direct damages* refer to the injury of plant parts (e.g., destruction of yield forming, storage, and reproductive organs); *indirect damages* cover changes in plant architecture, reduced growth and development, quality losses or aesthetics, and transmission of diseases. Indirect impacts can also occur through competition, parasitism, or predation of beneficial organisms

Table 6.2 Average yield losses due to non-native weeds in different crops and regions

Non-native weed	Life form	Origin area	Introduced area	Mech.[a]	Crop	Weed density	Yield losses (% mean ± SD)[b]	Number of references[c]
Ambrosia artemisiifolia (Asteraceae)	Therophyte	N America	Europe	C	Sugarbeet	105/m^2	76 ± 8.5	2
			Europe	C	Potato	105/m^2	30[d]	1
			Europe	C	Maize	8–26/m^2	48.2 ± 16.4	4
			Europe	C, I	Sunflower	10–100/m^2	57.8 ± 30.8	4
Avena fatua (Poaceae)	Therophyte	Temp. Asia	N & S America, Europe	C, A	Cereals	70–660/m^2	43.3 ± 25.1	3
			N America	C	Legumes	32/m^2	44.6 ± 11.1	2
Chenopodium album (Amaranthaceae)	Therophyte	Europe	N America	C	Maize	5–110/m^2	26.8 ± 11.2	3
			N America	C	Soybean	9–16/10 m^2	22.8 ± 7.6	2
Cirsium arvense (Asteraceae)	Geophyte	Europe	N America	C, I	Cereals	14–30/m^2	45.0 ± 12.7	3
			N America	C	Alfalfa	10–20/m^2	41[d]	1
Cynodon dactylon (Poaceae)	Geophyte	Trop. Africa	N America, Europe	C, A	Spring crops	200–400 stems/m^2	58.0 ± 18.2	1
Cyperus rotundus (Cyperaceae)	Geophyte	Trop. Asia and Africa	N & S America	C	Vegetable crops	75–125/m^2	58 ± 23.4	5
				C	Rice	–	50[d]	1
Echinochloa crus-galli (Poaceae)	Therophyte	Trop. Asia	N America	C	Spring crops and legumes	1–5/m^2	58.7 ± 36.7	3
Lolium rigidum (Poaceae)	Therophyte	Europe	C America Australia	C	Winter crops	300/m^2	31.8 ± 7.5	1

Parthenium hysterophorus (Asteraceae)	Therophyte	C America	Trop. Asia	C, A, I	Various crops	–	26.7 ± 12.6	3
Phelipanche ramosa[e] (Orobanchaceae)	Therophyte	Europe	C & S America	P	Legumes	–	50[d]	1
			S America	P	Tobacco			
Solanum elaeagnifolium (Solanaceae)	Geophyte	N America	N Africa, Australia	C, I	Various crops	5–6/m^2	46.4 ± 20.2	2
Sorghum halepense (Poaceae)	Geophyte	Temp. Asia	Europe, N America	C; A	Cotton	16–200 stems/m^2	71.2 ± 10.2	2
			Europe	C	Maize	100–200 stems/m^2	78.7 ± 25.8	3
			N & S America	C	Sugarcane	–	48.1 ± 23.3	2
			N America	C	Soybean	–	73.5 ± 20.5	1

[a]*C* competition, *A* allelopathy, *P* parasitism, *I* indirect effects
[b]Yield losses correspond to potential losses (see Fig. 6.1) based on experimental studies comparing weed-free field plots and plots with different quantities of weeds
[c] Indication of the number of studies on which the values are based
[d] The figures give the number of references on which the mean crop yield losses has been computed
[e]In most cases parasitic weeds are harmful to crops in their native range in the drier and warmer areas of Africa and Asia (*Striga*) and in the Mediterranean Basin (*Orobanche*, *Phelipanche*). A few species have been recorded outside their native range, for example, some species of *Cuscuta*, *Striga asiatica* in the USA, or *Phelipanche ramosa* in Australia and in America

(Willis 2007). Although allelochemical properties of weed residues are often short lived, their effects could be sufficient to favour the establishment of the weeds in the field at the expense of the crop. Allelopathy seems to be a main factor in the success of some non-native weeds, such as *Centaurea diffusa* in forage crops (e.g., *Pseudoroegneria spicata* or *Festuca scabrella*) in North America, or *Parthenium hysterophorus* in annual cereals (corn and sorghum) in Asia and Africa. Some parasitic weeds, such as witch weeds (*Striga* spp.), broomrapes (*Orobanche* spp. and *Phelipanche* spp.), or dodders (*Cuscuta* spp.), affect crop plants directly by connecting their haustorium to obtain water with its nutrients in the sap. Their derivation of nutritional requirements induces a short- or medium-term weakening of the annual crops, often continuing until harvest or leading to the death of the cultivated species (Parker 2009). The mechanisms that could explain the particular effects of non-native parasitic weeds on a new host crop encountered in the area of introduction are similar to those for crop pathogens (see Sect. 6.3.1.3).

6.3.1.2 Pests

The great diversity of arthropods feeding on plants demonstrate a remarkable diversity of lifestyles, mouthparts, and gut morphological adaptations to the food eaten. In relationship to the range of plant taxa used, monophagous insects feed on one plant taxon, oligophagous insects feed on few, and polyphagous insects are generalists that feed on many plant groups. Non-native arthropods injure plants directly through feeding or, indirectly through the transmission of plant pathogens. Feeding on green plants (phytophagy) causes plant tissue damages that are prejudicial for plant growth, survival, or reproduction of a variety of agricultural crops. Non-native arthropods include species that attack roots, stems, leaves, flowers, and fruits, either as larvae or as adults or in both stages. Leaf feeders may be external or they may mine tissues. There are many different ways that arthropod pests cause losses in plant yield by feeding directly on cultivated plants (see also Table 6.1).

- Leaf-chewing arthropods dominated by Lepidoptera, Coleoptera, or some myriapods, which can occasion severe defoliation, stem or root boring, and feeding on flower or seed structures
- Sucking arthropods, such as Hemiptera, Thysanoptera, or Acari, which drain plant resources by removing phloem or xylem contents or by sucking cell contents, leading to tissue necrosis, distortion, or stunting of shoots
- Leaf-mining species, mainly larvae of Hymenoptera, Lepidoptera, and Diptera, which cause leaf damage that appears as tunnels, blotches, or blisters
- Gall-making species (Diptera, Hymenoptera, Thysanoptera, and Acari), which alter, often substantially and characteristically, the morphology of plant parts

Many pests transmit economically important pathogens from infected to healthy hosts. Transmission of phytopathogenic viruses and bacteria by aphids, thrips, whiteflies, leafhoppers, planthoppers, treehoppers, fruit fly, flea beetles, psyllids, mites, and nematodes is well known.

6.3.1.3 Pathogens

A plant disease results from a compatible interaction that occurs as a result of a pathogen being able to overcome the resistance mechanisms of the host plant. Plant and pathogens sharing the same distribution area for long time periods have developed co-evolutionary mechanisms, often termed an arms race. Host resistance triggers an increase or a shift in pathogen virulence, which in turn enhances increased host resistance, and so on. This kind of plant–pathogen interaction was termed ‘old encounter’ by Robinson (1976). In crops, the co-evolutionary process includes breeding programs that involve selection for resistance to the main pathogens.

Introduction of a non-native pathogen in a given area results in a ‘new encounter’. Plant populations that have never encountered the pathogen, and therefore probably do not have resistance to it, are especially vulnerable to the newcomer, even more so when grown on large areas with limited genetic diversity, as is the case in most modern agro-ecosystems. In several cases, the new encounter is indeed a re-encounter: plants have been transported, pathogen free, to a new continent, where they have evolved or have been bred without pathogen pressure, therefore losing any original resistance factor. The introduction of the pathogen decades or centuries after the introduction of the plant can make the re-encounter fatal to the plant.

The most emblematic case of such a re-encounter is the inadvertent introduction of the oomycete causing potato late blight in Europe in the 1840s, more than three centuries after the introduction of the potato in Europe. Other significant examples are the introduction of chrysantheme rust, *Puccinia horiana*, in Europe (1900s); coffee rust, *Puccinia horiana*, and sugarcane rust, *P. melanocephala*, in the Americas; wheat stripe rust, *P. striiformis*, in Australia (1979); and of soybean rust, *Phakopsora pachyrhizi*, in the USA (2004). Such re-encounters can be expected to happen at some point when pathogens have the capacity for long-distance dispersal, via either wind or human transportation.

6.3.2 *Negative Consequences on Crop Production*

The relationship between weed or pest density or disease intensity and crop damage is critically dependent of the identity of the species and cultivars involved, as well as the cropping system and environmental conditions, with strong variation among years (Oerke 2006). Moreover, many reports of crop losses rarely differentiate the part caused by non-native species only. However, based on a few review articles that estimate average yield losses attributable to harmful organisms for the main crop species worldwide (Oerke 2006), and according to the relative proportion of native and non-native weeds, pests, and pathogens in different areas, a crude estimate of the impacts of non-native harmful organisms is possible.

The average potential losses (i.e., without crop protection) (see Fig. 6.1) are typically higher for weeds (23–43.6 % of attainable yield) than for animal pests (8.7–36.8 %) or for pathogens (8.5–21.2 %). However, because of higher efficacy of weed control, actual losses are almost similar among the three taxa: 7.5–10.5 %, 7.9–15.1 %, and 7.2–14.5 % for weeds, pests, and pathogens, respectively (Oerke 2006). In US agriculture, the loss from non-native weeds, pests, and pathogens was estimated to be $26.92, $14.4, and $21.5 US billion/year, respectively (Pimentel et al. 2005) (Fig. 6.3). In Western Europe, for example, in the UK, the production per hectare is greater than in North America, resulting in higher control costs relative to direct crop losses and higher impact of non-native pathogens compared to the other taxa (Fig. 6.3).

6.3.2.1 Weeds

It is difficult to simply categorise non-native weed species according to their impacts. The direction and magnitude of the effects of weed–crop competition for resources are related to their density and to environmental conditions, especially soil moisture or nutrients (Zimdahl 2004). The impact of a given weed also depends on the identity of the invaded crops, the duration of the interference, and the life history stage of the weed–crop system at which the interaction takes place (Vilà et al. 2004). Three traits are particularly relevant to the magnitude of the effect of competition on the crop.

- *Time of weed emergence compared to the crop species*: this is related to the duration of weed-free conditions. The effects of competition for resources are expected to be more important between taxonomically close species (e.g., *Ambrosia artemisiifolia* on sunflower; *Panicum* spp. on maize). In addition, taxonomic proximity makes selective weeding control methods (chemical and mechanical, seed sorting) more difficult. For example, large infestations of *A. artemisiifolia* can induce a complete destruction of sunflower fields (Table 6.2). In the EU, the economic cost of *A. artemisiifolia* through the loss of agricultural production has been estimated to €1846 million/year.
- *Growth rate*: weeds that are able to grow tall, reach high cover, or achieve rapid lateral spread will gain a competitive advantage, which is why perennial weeds such as *Cirsium arvense* or *Sorghum halepense* are so harmful in cereal crops. The reserves stored in their underground organs make them able to grow faster and more vigorously than the annual crops and ensure survival and escape from chemical treatments and superficial tillage. For example, 10–30 shoots/m^2 of *C. arvense* are sufficient to cause more than 40 % yield losses, with crop loss exceeding 70 % in dense patches (Tiley 2010).
- *Weed size relative to that of the crop*: differences in size between weed and crop species are thought to be a robust predictor of yield losses. This is one of the factors that make *Avena fatua* (that reaches up to 150 cm height) one of the most important and competitive grass weeds of winter and spring cereals (~85 cm height on average), resulting in 5 % yield loss from as few as 5 plants/m^2 (Beckie et al. 2012). In the prairie provinces of Canada, annual losses from *Avena fatua* vary from CAN$120 million up to CAN$500 million (Beckie et al. 2012).

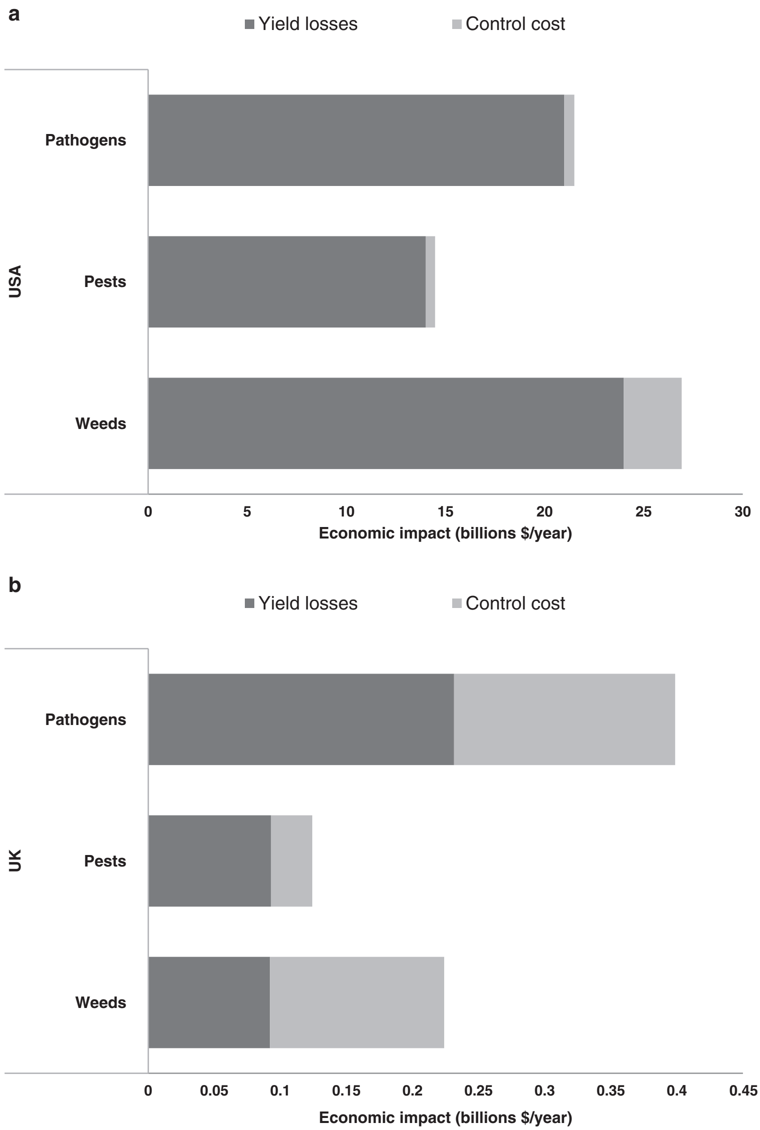

Fig. 6.3 Economic impacts of non-native weeds, pests, and pathogens on crops (billions $/year) in (**a**) the USA (data from Pimentel at al. 2005) and (**b**) the UK (Data from Williams et al. 2010)

Globally, parasitic weeds are not common; threatened crops represent about 4–5 % of the world's arable land. However, where present, these weeds can be very impressive in their effects. In the USA, it was estimated that the spread of *Striga asiatica* following its introduction in 1956 would have led to weed control costs of US$1 billion per year, beside total losses of yield of at least 10 % each year. Across four decades, the cost of eradication of *S. asiatica* has totalled US$250 million.

Fig. 6.4 Strong density of common ragweed, *Ambrosia artemisiifolia*, in a weeded sunflower field (France, August 2015) (Photograph by R. Bilon © Observatoire des ambroisies)

Although several weeds impact crop yield through both competition and allelopathy (Table 6.2), the latter mechanism is considered the primary one in only a few species; for example, crop losses of up to 40 % reported for *Parthenium hysterophorus* in Asia and Africa occur primarily through allelopathic effects.

Finally, invasive non-native weeds can also have indirect effects on the quality of farm products or even on the whole cropping system. Even at low density, seeds or leaves in harvested products (grain or forage) can cause a decrease in quality or problems of human or livestock poisoning (e.g., *Datura stramonium*). The efficiency of control of *Ambrosia artemisiifolia* is sometimes so poor that farmers avoid introducing sunflower in their rotation when ragweed seed density is too high (Fig. 6.4). In the early days of settlement in North America, the difficulty in controlling *Cirsium arvense* was such that it often led to the abandonment of whole farms (Tiley 2010). In Morocco, agricultural land infested with *Solanum elaeagnifolium* results in a decrease by 25 % in the rental and resale of infested fields.

6.3.2.2 Pests

The combination of the numbers of the pest present, their development stage, and the duration of the pest attack on the crop influences the intensity of crop losses. Full costs of most potential invasive arthropods are still poorly known, and most risk

Fig. 6.5 Adult of brown marmorated stink bug, *Halyomorpha halys*, feeding on an apple. *Halyomorpha halys* attacks tree fruit, small fruit, vegetables, and ornamentals. In tree fruit, economic damage has resulted in increased production inputs and secondary pest outbreaks in affected countries (Photograph by J.-C. Streito © INRA Montpellier)

assessment studies rely on expert judgment or rudimentary analytical approaches. A few well-known examples are described here.

One of the first major non-native pests to affect the European economy was the American vine phylloxera, *Daktulosphaira vitifoliae*. In the late nineteenth century, this small sap-sucking insect completely destroyed nearly one-third of the French vineyards, that is, more than 1,000,000 ha, with incalculable economic and social consequences. At the beginning of the twentieth century, the introduction of the boll weevil, *Anthonomus grandis*, from Mexico to North America resulted in billions of dollars of damage and the almost complete eradication of the cotton crop in the USA. The most widespread insect pest throughout the US corn belt has been the European corn borer, *Ostrinia nubilalis.* This pyralid moth was accidentally introduced into eastern USA in 1917 and subsequently spread with devastating results. Losses are estimated to be US$1 billion per year (Hutchison et al. 2010). The pest is now controlled through reductions in its populations resulting from genetically engineered Bt maize.

Any continent is now facing major challenges from increasing non-native arthropods attacking crops. The brown marmorated stink bug, *Halyomorpha halys*, is a polyphagous sucking insect native to Asia that invaded the USA in the mid-1990s. In 2010, it resulted in up to US$37 million losses for apple alone in the mid-Atlantic region (Fig. 6.5). Some stone fruit growers lost 90 % of their crop (Leskey et al.

2012). The rice water weevil, *Lissorhoptrus oryzophilus*, was accidentally introduced from North America into Japan on infested rice straw in 1976, with subsequent yield losses of 41–60 % caused by root pruning and chlorosis of seedlings. *Drosophila suzukii* is thought to be a native of eastern and southeastern Asia. It was first detected in mainland USA in 2008 and simultaneously in Europe. The larval stage of this small drosophilid infests and develops in undamaged ripening fruits, rendering the fruit unmarketable. Preliminary studies in the USA (Bolda et al. 2010) indicate an annual loss of more than US$500 million in five affected crops (strawberries, blueberries, raspberries, blackberries, cherries) in three states (California, Oregon, and Washington). In France, yield loss estimates from 2013 observations range from negligible to 100 % on cherry crops.

6.3.2.3 Pathogens

Several plant pathogens directly decrease yield by killing crop plants (blights, rots) or decreasing biomass production (rusts, powdery mildews), but not killing the plants. Because of their explosive spatiotemporal dynamics and environmental plasticity, pathogens can annihilate yield in plots not protected by either genetic resistance or pesticide sprays. The Asian soybean rust, introduced in the Americas in 2001, claimed 5 % of the annual production in Brazil; in the USA, the annual net economic losses were anticipated to range from US$240 million to US$2 billion, depending on the severity and extent of subsequent outbreaks (Fig. 6.6). Increased early warning, monitoring, and education, however, resulted in the control of the disease, saving farmers more than US$200 million annually in unnecessary fungicide applications (Sikora et al. 2014). In Switzerland, the control of fire blight, a quarantine invasive disease of Maloideae caused by the bacterium *Erwinia amylovora*, has cost 29 million Swiss francs over a 10-year period.

Plant pathogens with less direct or even no significant effect on yield can also decrease production by making the crop plants unsuitable for marketing. Vegetables, fruit, and flowers with disease symptoms (spots, chlorosis) lose commercial value and are banned from use in industrial processing. Potatoes with malformation induced by the Potato spindle tuber viroid will no longer fit the processing standards and will be discarded. The generalised spread of the disease to Europe, where it now occurs only sporadically, would cause an annual loss for the producers of €567 million and require control measures costing €118 million (Soliman et al. 2012). Finally, some pathogens produce secondary metabolites that represent a risk for cattle and human health. Ergotism is an historical issue that is currently re-emerging, and the production of carcinogenic toxins by several species of *Fusarium* infecting wheat is the subject of norms and regulations all over the world.

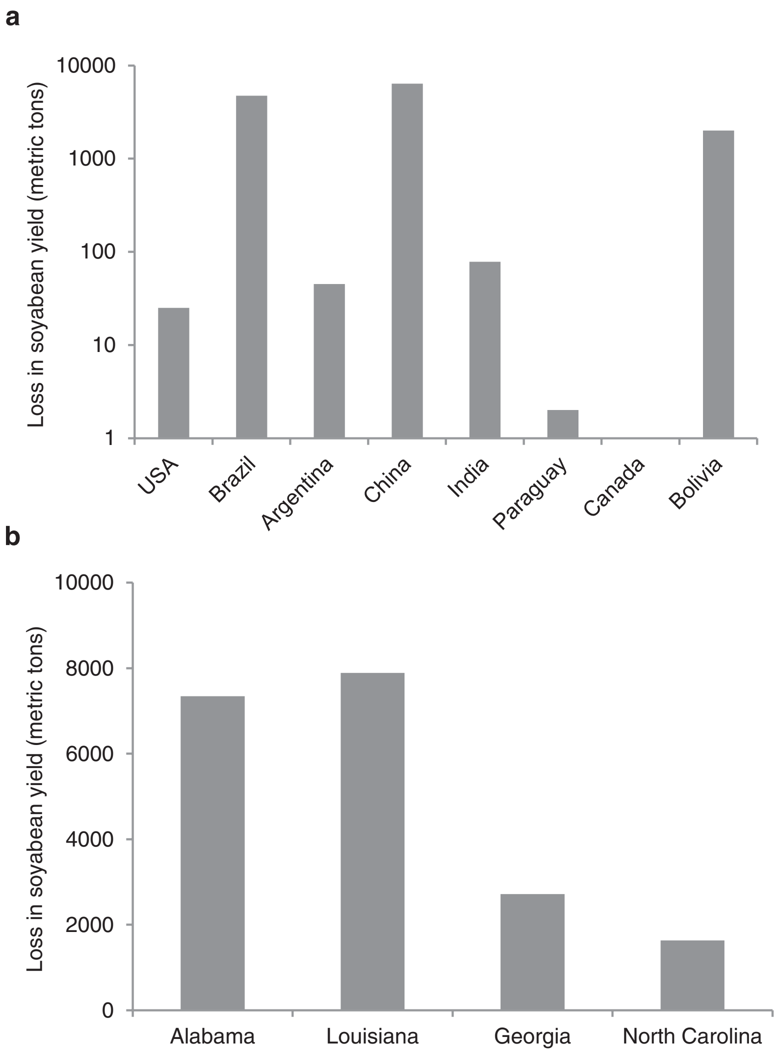

Fig. 6.6 Estimated reduction of soybean yields caused by soybean rust in 2006 in (**a**) the world's top eight soybean-producing countries (thousand metric tons; note the logarithmic vertical scale) and (**b**) the USA top four soybean-producing states (metric tons; note the linear vertical scale) (Data from Wrather et al. 2010)

6.4 Conclusions

Several economic assessments have stressed that agriculture is the sector being most affected by the introduction of non-native species. Introduced weeds, pests, and pathogens cause annual losses to world agriculture estimated between US$55 billion and US$248 billion (Pimentel et al. 2001). Of the US$120 billion/year of damages associated with non-native species in the USA, US$62.2 billion/year (52 %) are caused by species invading crops (Pimentel et al. 2005). In UK, 64 % of the £1.67 billion/year economic impact of non-native species concerns agriculture (Williams et al. 2010). Pesticide application has traditionally been an effective and economical means of reducing crop losses and ensuring that new species do not proliferate in arable land. However, overdependence on pesticides has negative impacts on the environment and has dramatically favoured the development of resistant biotypes. To reduce crop losses and arable land vulnerability to invasions, a more sustainable, integrated, and holistic approach is needed (Harker et al. 2005): this should include higher prevention measures at the international level (i.e., pathways risk assessment, surveillance, early detection, and rapid eradication) and restore, as much as possible, ecological regulation (competition, predation, parasitism) at the landscape and field level. This integrated approach will also require ensuring optimal crop canopy health, selecting competitive and resistant cultivars, optimising seeding density and careful seed placement, strategic fertilisation and watering, but also more diverse crop rotations.

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