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REVIEW ARTICLE

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Control of crop diseases through Integrated Crop Management to deliver climate-smart farming systems for low- and high-input crop production

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Abstract

Crop diseases affect crop yield and quality and cause significant losses of total food production worldwide. With the ever-increasing world population and decreasing land and water resources, there is a need not only to produce more food but also to reduce agricultural greenhouse gas (GHG) emissions to mitigate climate change and avoid land use change and biodiversity loss. Thus, alternative climate-smart farming systems need to adapt to produce more food per hectare in a more sustainable way than conventional high-input farming systems. In addition to breeding new high-yielding cultivars adapted to future climates, there is a need to deploy Integrated Crop Management (ICM) strategies, relying less on synthetic inputs for fertilization and crop protection and less on fossil fuel-powered machinery to decrease yield losses due to pest and pathogens and guarantee food security. In this review, we compare some low-input farming systems to conventional agricultural systems with a focus on ICM solutions being developed to reduce synthetic inputs; these include crop genetic resistance to pathogens, intercropping, canopy architecture manipulation, and crop rotation. These techniques have potential to decrease crop disease frequency and severity by decreasing amounts and dispersal of pathogen inoculum and by producing microclimates that are less favourable for pathogen development, while decreasing GHG emissions and improving environmental sustainability. More research is needed to determine the best deployment of these ICM strategies in various cropping systems to maximize yield, crop protection, and other ecosystem services to address trade-offs between climate change and food security.

KEYWORDS
climate change, crop rotation, food security, intercropping, organic agriculture

1 | INTRODUCTION

Land-based food production is fundamental to the livelihood and welfare of humans. There are limited numbers of plant species that are domesticated, adapted, and cultivated to produce food to feed the world population. Among the food crops, wheat, rice, maize, and soybean combined contribute two thirds of total human calorie intake (Zhao et al., 2017). Crop production is characterized by seasonality and constant attention to detail to maintain crop growth and health throughout the growing season. It is often subject to challenges from uncontrollable weather forces or uncertainties in effectiveness of fertilizer applications (abiotic stresses) or in successful control of diseases, pests, or weeds (biotic stresses). Crop yield losses from diseases have been estimated at between 20% and 40% in important food crops, despite use of crop protection measures (Oerke, 2006; Oerke & Dehne, 2004; Savary et al., 2019). The sizes of total potential or actual production losses and economic losses due to biotic stresses can then be estimated, as shown for five staple food crops at a world scale in 2018 (Table 1). Decreasing global production losses in these food crops will help to reduce the number of severely food insecure people, which was estimated in 2020 at 927.6 million in the world and 12.8 million in Europe (FAOSTAT, 2020). It will thus help to accomplish the 17 UN Sustainable Development Goals (SGDs; e.g., zero hunger, good health and well-being; https://sdgs.un.org/goals). The vulnerability of food security to crop pathogens prompted the establishment of global surveillance systems to expedite global responses to crop disease epidemic outbreaks to minimize the risk to food supplies (Carvajal-Yepes et al., 2019). This reinforces the need for coordinated international research efforts to understand and manage crop diseases caused by pathogens that rarely respect national boundaries (Nelson, 2020). The "One Health" concept was developed to "promote sustainable ecosystemic services linked to the concept of health (human, animal and ecosystem) and to social stability" (Destoumieux-Garzón et al., 2018). Even if at first it was developed for zoonoses, it is now extended to environmental health and then to plant diseases (Morris et al., 2022).

The world's population exceeded 7.7 billion in 2020; it is still increasing and expected to reach approximately 10 billion by 2050 (Tilman et al., 2011; UN, 2019) (Figure 1). Meanwhile, the expansion of world agricultural land area since records began in 1961 stopped in 2001 at 4882.2 Mha. However, the agricultural land area per capita has continued to decline every year since 1961. To satisfy the ever-growing food demand, global agricultural production must increase by 70% by 2050 (Carvajal-Yepes et al., 2019). Furthermore, changing diets to consume more plant-based foods to mitigate climate change, together with increased environmental degradation and awareness of animal welfare, will entail sustained intensification or expansion of the existing agricultural land area, if increased food production is warranted in developed counties such as those in Europe (Poore & Nemecek, 2018). A conversion of land to agriculture will lead to an increase in anthropogenic CO_2 emissions (Lynch et al., 2021). Moreover, human economic development and related activities have increased concentration of anthropogenic greenhouse gases (GHG) in the atmosphere and modified the climate of the earth (see Section 8.1 for more details regarding GHG from agricultural systems). As a result, the annual atmospheric CO_2 concentration has increased every year since 1959 (NOAA/GML, 2021). It has increased at an annual rate of 2.2 ppm for the past 20 years and reached 414 ppm in 2020. The global mean annual temperature over land has increased, with the seven greatest temperature increases compared to the long-term mean from 1901 to 2000, ranging from 0.74 to 0.98°C, occurring in the last decade (2011–2020) (Figure 2; NOAA/GML, 2021). When compared with the observed temperature records for the same period maintained at Rothamsted Research, Harpenden, UK (Perryman et al., 2020), temperature increase followed a similar trend even though the temperature difference from the mean varied more at Rothamsted Research, implying that there can be more extreme temperatures under climate change at local scales than at a global scale. Increasing temperature is not only threatening crop production (Jaggard et al., 2010; Lobell & Gourdji, 2012; Zhao et al., 2017) but also exacerbating the decrease in available arable land per capita as sea levels increase under climate change (Beddington, 2010). In Europe, it was estimated that, relative to those in 2000, summer and winter temperatures are likely to increase by 3.5°C and 4.7°C, respectively, by 2050 (Bastin et al., 2019). Recognizing the risks and impacts of climate change, the

TABLE 1 Crop protection in relation to food security, shown for total worldwide production of rice, wheat, maize, potato, and soybean crops, with actual losses (with crop protection), and potential losses if no crop protection measures were used to control all biotic stresses or to control pathogens causing diseases, estimated for each crop

	Actual crop losses with crop protection				Potential crop losses without crop protection			
	All biotic stresses		Pathogens		All biotic stresses		Pathogens	
Crop	Mt	$ billion	Mt	$ billion	Mt	$ billion	Mt	$ billion
Rice	28.0	114.6	7.7	31.6	58.2	238.6	10.2	41.8
Wheat	21.4	47.1	8.3	18.2	38.3	84.2	11.9	26.3
Maize	35.6	75.5	9.8	20.7	45.9	97.4	10.8	22.9
Potato	14.8	38.4	5.4	13.9	27.8	72.0	7.9	20.3
Soybean	8.7	25.9	3.0	8.9	20.0	59.9	3.7	11.0

Note: Estimates of total crop production losses in million tonnes (Mt) and total economic losses in billion US dollar ($) obtained by multiplying proportions of crop yields lost to all biotic stresses or to pathogens (obtained from Oerke, 2006) by world total production of these crops in 2018 (from FAOSTAT, 2020). All biotic stresses include weeds, pests, pathogens, and viruses; pathogens include fungi and bacteria.

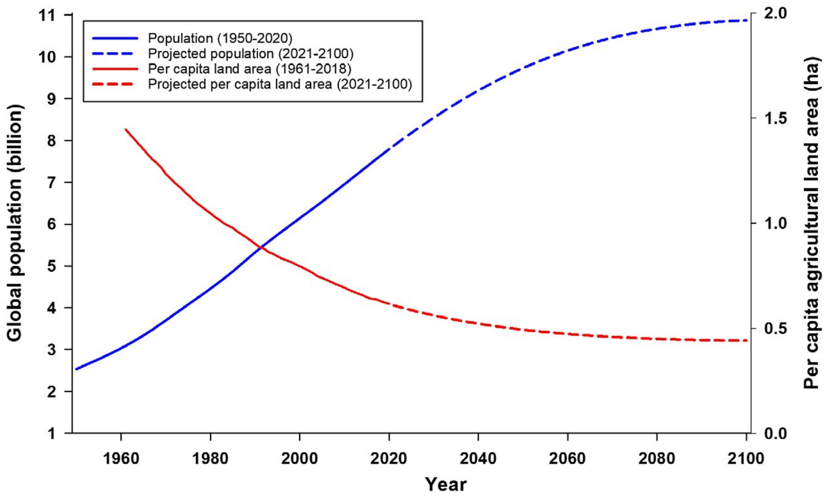

FIGURE 1 The world population from 1950 to 2020 and the projected world population from 2021 to 2100 (blue line); and the per capita agricultural land area from 1961 to 2018 and the projected per capita agricultural land area from 2021 to 2100 (UN, 2019). The projected per capita agricultural land area was calculated by fixing the world agricultural land area averaged in the latest five years (2015–2019) from 2021 to 2100

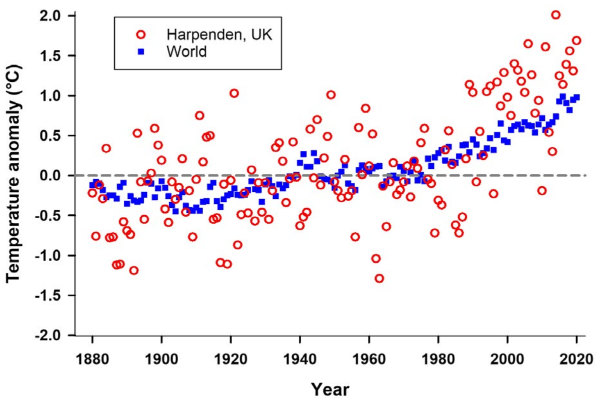

FIGURE 2 Annual land surface temperature anomalies in 1880–2020 compared to mean temperature in the period 1901–2000 over the globe (NOAA/GML, 2021) and at Rothamsted Research in Harpenden, United Kingdom (Perryman et al., 2020). Temperature points below the grey zero line were less than the mean temperature in the period 1901–2000 while temperature points above the grey zero line were greater than this mean temperature

Paris Agreement (United Nations Framework Convention on Climate Change, 2015) was adopted and signed by many countries in the United Nations to mitigate climate change. The long-term goal within the agreement is to keep the global mean temperature increase to much less than 2°C above the pre-industrial temperature, but preferably to achieve a temperature increase of less than 1.5°C by 2100. In addition, the United Nations (UN) established 17 SDGs to be achieved by 2030. Among these, the agricultural sector is required to contribute to ending hunger, achieving food security and improved nutrition through sustainable agriculture (SDG 2) while protecting, restoring, and promoting sustainable use of terrestrial ecosystems and halting biodiversity loss (SDG 15) and, at the same time, taking actions to mitigate and adapt to climate change (SDG 13). In particular, the second goal, "zero hunger", is directly linked to agricultural production but unfortunately will be difficult to achieve (FAO et al., 2020).

Thus, food security is facing the joint threats posed by increases in global population, more climate change-related extreme weather events, and risks of increasing occurrence of severe crop disease epidemics (Chaloner et al., 2021; Rosenzweig et al., 2001; Saunders, 2021). Increasing temperatures have significantly affected crop growth and development, reducing yields of major food crops. They have also altered pathogen distribution and patterns of pathogen infection, making crop disease epidemics more severe and less predictable (Newbery et al., 2016). There is a need for crops with greater yields that are also more nutritious, pest and pathogen-resistant, and "climate smart" (Hickey et al., 2019). Lipper et al. (2014) defined climate-smart agriculture as an approach to transform agricultural systems to support food security under climate change, involving all the members of the agricultural sector (farmers, researchers, stakeholders, and policy makers). As a consequence of climate change and change in human diet, there will also be opportunities to grow new crops more widely in Europe, such as quinoa or soybean in the United Kingdom (Coleman et al., 2021).

Thus far, the increases in crop yields achieved from growing the crop cultivars bred since the Green Revolution in the 1960s have kept pace with food demands of large, growing populations. However, these high-yielding cultivars were bred to be grown in monoculture suitable for mechanization and adapted to high inputs such as mineral fertilizers, fungicides, herbicides, and sometimes irrigation (Byerlee, 1996). Moreover, these cultivars are susceptible to pathogens that cause diseases and the chemicals used to protect them can degrade natural resources such as soil, water, and biodiversity, leading to limited growth in crop productivity (Burney et al., 2010). To address climate change and reduce greenhouse gas emissions to net zero by 2050, new sustainable crop production systems are required to maintain/improve soil health, soil carbon sequestration, and ecosystems to produce more food with less land (less carbon emission from soil conversion to agricultural land) and less use of synthetic products (less pollution from residues) (see Section 8.1 for more details regarding GHG from agricultural systems). Sustainable routes towards increasing food production to ensure food security are necessary, whether they are nature-based or dependent on chemicals, or both (Godfray & Garnett, 2014; Stafford et al., 2021). The importance of crop diseases relates to the fact that food shortages can result in massive economic disruption, social instability, and human starvation in many cases. These include the potato famine in Ireland caused by the potato pathogen *Phytophthora infestans* (Fry et al., 2015) and the Bengal rice famine in present-day Bangladesh and India, caused by *Helminthosporium oryzae* (Padmanabhan, 1973). The challenge for plant pathologists will then be to maintain current disease control and further reduce crop losses in an environmentally sustainable way (using less chemical inputs both for disease control and for plant nutrition). Integrated Crop Management (ICM) solutions, based on new crop protection products and methods and new interdisciplinary knowledge, will be needed (Jeger et al., 2021). In this review, we will focus on the main fungal and fungal-like diseases on arable crops in Europe. Our aims are:

- to discuss challenges associated with future climate changes, and conventional (high-input) agriculture and low-input agricultural systems
- to present ICM solutions and technologies to deliver food security while reducing agricultural GHG footprint
- to summarize advantages and disadvantages of research findings that contribute to our understanding on how low-input agricultural practices can affect crop yields and diseases
- to provide recommendations on how to deploy climate-smart cropping systems and to prioritize future research needed to improve their efficiency and facilitate their utilization.

2 | CLIMATE CHANGE IMPACTS ON CROPS AND PATHOGENS

Climate change will directly affect crop pathogens and the diseases they cause. This topic has been widely investigated and reported for the last few decades, even under controlled conditions, for example, free air concentration enrichment (FACE) systems and open-topped chambers (Eastburn et al., 2011) or with modelling studies (e.g., Bregaglio et al., 2021; West et al., 2012). Juroszek et al. (2020) reported that there have been more than 100 review articles on this topic in the last 30 years, classifying them by weather parameters discussed, geographic range, and pests and pathogens studied. In Europe, temperatures are expected to increase, with more severe extreme weather events (late spring frosts, summer droughts, increased windspeeds) and less rain in southern Europe, which will then require more irrigation (Hristov et al., 2020). Future crops will need to be adapted to these hotter/drier environments (Olesen et al., 2011). Climate change is also expected to have a CO_2 fertilizer effect on C_3 plants (Donatelli et al., 2015; Hristov et al., 2020). However, Ortiz-Bobea et al. (2021) observed that, despite this effect, recent climate change has decreased growth in agricultural productivity since the 1960s. Climate change will also have direct impacts on plant pathogens (Table 2). Increased winter temperatures will not only extend the crop-growing season but also enhance winter survival of pathogens, potentially producing early onset of epidemics (Newton et al., 2011). Climate change is also expected to expand pathogen distribution to higher latitudes (Bebber et al., 2013; Chaloner et al., 2021). A warmer environment may also be favourable for the emergence of new pathogens (Anderson

TABLE 2 Climate change impacts on environment, crops, and diseases in Europe

Environment[a]	Crops[a]	Diseases	References
Changes in temperature			
Warmer winter	Change in crop phenology	Pathogen survival over winter, migration into areas previously too cold, earlier spore release/change in pathogen phenology	Newton et al. (2011)
Increased temperatures, spring and summer	More irrigation/drought tolerant cultivars needed, new crops/crop locations changing	Pathogen adaptation, new diseases, resistance gene expression might be impacted	Anderson et al. (2004); Miedaner and Juroszek, (2021a); Ristaino et al. (2021)
Stronger winds		Increased pathogen spread with greater concentrations of spores	Garrett et al. (2011)
Changes in rainfall patterns			
Decreased rainfall amount in south and central Europe	Increased need for irrigation, crop breeding for drought tolerant crops	Adaptation to drier environment/ shorter leaf wetness duration for infection	Velásquez et al. (2018)
Increased rainfall amount in northern Europe		More severe epidemics	Garrett et al. (2006); West et al. (2012)
Increased CO_2 concentration	Fertilization effect for C_3 crops	Changes in pathogen sporulation	Eastburn et al. (2011); Newton et al. (2011); Pangga et al. (2011)

[a]Based on Hristov et al. (2020) and Olesen et al. (2011).

et al., 2004; Ristaino et al., 2021). Increased temperatures in spring and summer might lead pathogens to evolve to survive at higher temperatures (Miedaner & Juroszek, 2021a, 2021b; Velásquez et al., 2018). For example, new wheat yellow rust (*Puccinia striiformis* f. sp. *tritici*) races such as *Warrior* (*PstS7*) are better adapted to warmer environments than older races (Vallavieille-Pope et al., 2018). Moreover, increased temperatures during the growing season might also weaken the plant host, due to abiotic stresses or loss in effectiveness of resistance genes at higher temperatures (Miedaner & Juroszek, 2021a). For example, Huang et al. (2006) observed that the oilseed rape resistance gene *Rlm-6* against *Leptosphaeria maculans* was no longer effective as temperature increased from 15 to 25°C. The increase in atmospheric CO_2 concentration will also directly influence fungal pathogens by influencing their aggressiveness and increasing the reproduction and growth of some of them (Eastburn et al., 2011; Luck et al., 2011; Pangga et al., 2011). Warmer temperatures will also generate stronger winds. These winds could transport greater concentrations of airborne pathogen spores over longer distances (Garrett et al., 2011). With drier environments in southern Europe, more irrigation will be needed. This will increase canopy moisture and hence favour disease epidemic development (Swett, 2020). Moreover, the type of irrigation system is also important, because sprinkler irrigation can also increase dispersal of splash-dispersed pathogens (Dixon, 2015). An increase in rainfall frequency will have similar effects (Garrett et al., 2006; Luck et al., 2011; West et al., 2012).

All these changes threaten current farming systems. Conventional agriculture will need to adapt and evolve to deliver sustainable intensification to address these risks and ensure food security (Saunders, 2021).

3 | CONVENTIONAL AGRICULTURE

High-input conventional agricultural systems, for example as developed in the United Kingdom during the last half century, are based on the management of a few monoculture crops (Table 3). To maintain high yields and limit crop losses, conventional farming systems rely on extensive use of synthetic pesticides and fertilizers, and irrigation. The farmers usually use machinery powered by fossil fuel (Figure 3a) to apply these products, which increases the contribution of released CO_2 from farming systems (Lynch et al., 2021). In Europe, the annual agricultural use of nitrogen (N) fertilizers increased between 1961 and 1988 (from c. 5000 Mt to c. 28,000 Mt) before decreasing to c. 14,000 Mt by 1995 and staying relatively stable since then (Figure 4a). Nitrous oxide (N_2O) emissions resulting from the use of N fertilizers (direct and indirect emissions) followed a similar pattern and are now c. 310 kt p.a. (Figure 4b). Use of fungicides and bactericides in Europe has been relatively constant from year to year since 1990, at around 200 kt p.a. (Figure 4c). At the same time, there has been a decrease in arable land area in Europe, from 32% in 1960 to 24.7% in 2018 (World Bank, 2018), which means that, although there has been no overall change in use of N fertilizers and fungicides and bactericides, there has been an increased use per arable land unit. This has been due not only to loss of arable land, a process in which urban areas (e.g., housing) occupy agricultural lands, but also to rewilding of arable land areas or use of arable land for second generation bioenergy crops such as short rotation coppice willows (Figure 3c). Conventional tillage (Figure 3b), which aims to prepare the seedbed before sowing and bury weeds and previous crop residues, can also affect soil quality, increase soil erosion, and decrease soil carbon sequestration, and hence release CO_2 to the atmosphere (Arriaga et al., 2017).

With widespread use of fungicides, plant pathogens started to develop insensitivity/tolerance against them (Corkley et al., 2022; Mikaberidze et al., 2017). At the same time, some widely used fungicides have been banned (e.g., chlorothalonil), decreasing the number of available fungicides, threatening the economic viability and stability of growing important crops such as oilseed rape and sugar beet and increasing the need to develop other solutions

TABLE 3 Main practices in conventional and low-input (organic, conservation agriculture) farming systems and Integrated Crop Management practices that can be applied to reduce fungicide use in all the different systems

Farming system	Practices
Conventional agriculture	Monoculture, extensive use of synthetic fertilizers and pesticides, deep tillage
Organic agriculture	No use of synthetic inputs or genetically modified crops, reduced tillage, relies on agroecosystem services, certified crops only
Conservation agriculture	Minimum soil disturbance by tillage (no-till if possible) and cultural operations; all year-round organic matter cover over the ground; diversified crop rotations
Integrated Crop Management	Use of preventive or pathogen suppression methods such as crop rotation, pathogen-resistant/tolerant cultivars; monitoring of pest and pathogens; decision support tools to guide application of plant protection measures; use non-chemical methods if possible; pesticides used should be specific to the organism and with few side effects on human health, non-target organisms, and the environment; use smallest dose applicable to avoid impacts on environment and development of pathogen insensitivity

FIGURE 3 Examples of common practices in conventional agriculture, including fertilizer spreading (a) and deep tillage by ploughing (b), and of alternative strategies to increase biodiversity for marginal soils with bioenergy crops such as willow (c) or wild flowers in crop field margins (d) (Credits (a) and (b): WikiCommons, https://commons.wikimedia.org/wiki/Main_Page)

(Dewar & Qi, 2021). Using crop cultivars with genes for resistance against pathogens can help but, as for fungicides, plant pathogen populations usually evolve to render them ineffective (see more details in Section 5.1). In addition, there can be re-emergence of crop diseases caused by pathogens for which resistance breeding was no longer a priority. An important example is wheat stem rust (*Puccinia graminis* f. sp. *tritici*) in western Europe, which was eradicated during the second part of the 20th century; thus, the common current wheat cultivars in Europe lack resistance genes against the pathogen strains that have caused the recent epidemics (Lewis et al., 2018).

4 | ALTERNATIVES TO CONVENTIONAL FARMING

There is a need for conventional agricultural systems that use less synthetic crop protection products and fertilizers with better use efficiencies, and then to change to alternative farming systems relying more on ecosystem services, such as wildflowers in field margins (Figure 3d). These systems are sometimes referred to as low-input farming systems as it is expected that they will use less chemicals and less machinery than conventional systems (Biala et al., 2008). However, these low-input systems will need not only to maintain yield production in the short term but also to produce increased yields in the longer term, which is sometimes referred to as sustainable intensification. Sustainable intensification can be defined as the process to produce more food whilst delivering environmental and social benefits (Dicks et al., 2019).

One of the most familiar alternative systems is organic agriculture (Table 3). It is a system that does not use synthetic inputs (such as mineral fertilizers and crop protection chemicals) or genetically modified crops for crop production. The total organic area (certified areas and areas under conversion) in the European Union (27 countries) covered approximately 13.8 million ha in 2019 (increase of 46% from 2012), which corresponds to 8.5% of the total agricultural area (Eurostat, 2021). Regarding crop protection, disease management is based on methods to improve agroecosystem health (e.g., biodiversity and soil health) by using crop rotation, intercropping, resistant cultivars if available as certified organic crops, addition of manure and compost, and decrease in soil tillage (van Bruggen et al., 2016). However, despite its environmental benefits, there is a yield gap between organic and conventional agriculture, with smaller yields in organic systems (Meemken & Qaim, 2018). On average, there is a decrease in yield of 16% for organic agriculture compared to conventional farming (Knapp & van der Heijden, 2018). However, this yield gap is dependent on the crops and area where they are grown. Pulse crops such as pea do not require nitrogen fertilization and then have smaller yield gaps than cereals (de Ponti et al., 2012). For example, these authors observed, based on a literature search, an average yield gap of 8% and 15% for soybean and pea, respectively, whereas for rye and wheat, the average yield gaps were 24% and

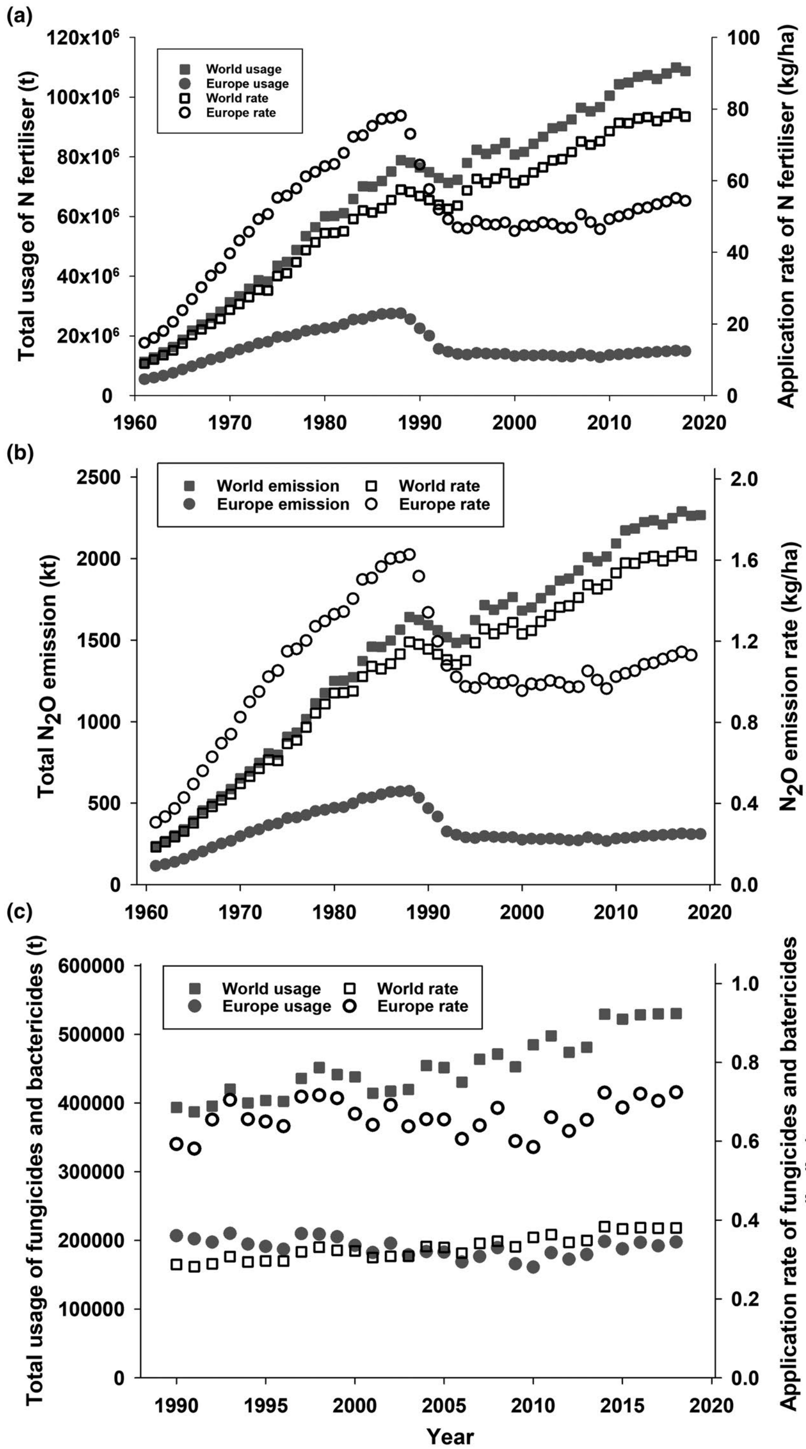

FIGURE 4 Total annual nitrogen (N) fertilizer inputs in 1961–2018 (a), total annual nitrous oxide (N_2O) emissions in 1961–2018 (b) of thousand tonnes (kt) from nitrogen mineral fertilizer inputs and total annual fungicide and bactericide inputs in 1990–2018 (c) for agricultural use in the world and in Europe (FAOSTAT, 2020). The input rates of N fertilizer were calculated by dividing the total N fertilizer inputs by the total arable land areas in the world or in Europe; the N_2O emission rates per hectare were calculated by dividing the total N_2O emissions by the total arable land areas in the world or in Europe; and the application rates of fungicide and bactericide were calculated by dividing the total usage by the total arable land area in the world or in Europe, respectively

27%, respectively. There is then a need for new crop cultivars and management techniques in organic agriculture to address this yield difference.

Another alternative farming system is conservation farming (Table 3). The aim of conservation agriculture is to improve soil health and limit soil erosion, and it is based on three principles (Giller et al., 2015; Kassam et al., 2009):

- minimizing soil disturbance by tillage (no-till if possible) and limiting cultivation operations
- maintaining organic matter cover over the ground throughout the year (use of cover crops or previous crop residues left on field)
- diversifying crop rotations, including nitrogen-fixing legumes in the rotation sequence.

It is expected from this to improve soil organic carbon content and decrease GHG emissions and soil erosion, compared to conventional agricultural systems. Conservation agriculture is often associated with regenerative agriculture (Giller et al., 2021; Newton et al., 2020).

These low- and high-input agricultural systems are not entirely independent, and some practices can be shared at the discretion of the farmer. However, a decrease in fertilization or in tillage could indirectly impact crop diseases (see Section 6).

Regarding crop protection, these systems need to rely on ICM, also referred to as integrated pest management (IPM), to decrease yield loss due to diseases by favouring mechanical, physical, and natural disease control and using chemical control only as a last resort (Table 3). Here, we use the term ICM to avoid any confusion with the definition of the term "pest", as suggested by Jeger et al. (2021). ICM principles are defined in Europe by the EU "Sustainable use of pesticides" directive (Directive 2009/128/EC-Annex III) and include:

- the use of preventive or suppression methods such as crop rotation, pathogen-resistant/tolerant cultivars
- the monitoring of pests and pathogens
- decision support tools to guide application of plant protection measures
- the use of non-chemical control methods, if possible
- pesticides used should be specific to the problem target organism, with as few side effects as possible on human health, non-target organisms, and the environment
- use as small a dose as possible to avoid impacts on the environment and development of pathogen insensitivity.

These techniques usually rely more on resistance against, avoidance, or elimination of the pathogen than on remediation with fungicide applications (He et al., 2016) and be applied or are already used in conventional agriculture as well.

5 | RECENT TRENDS IN CROP PRODUCTION PRACTICES WITH LOW CHEMICAL INPUTS TO MITIGATE CLIMATE CHANGE AND THEIR IMPACTS ON PATHOGEN POPULATIONS AND DISEASE EPIDEMICS

A main purpose of crop disease management is to protect/improve crop health to achieve the potential yields and minimize yield losses (He et al., 2016). Crop production systems are usually determined by the regional climate, local topography, and socioeconomic factors. However, distinctions have often been made between low-input extensive and high-input intensive cropping systems. Although detailed critical examination of these distinctions is still required, principles of disease management methods can apply to both low-input and high-input crop production systems (Table 4). There is also a need to improve deployment of these strategies at a larger scale than the farm scale to gain in efficacy (see Section 8.2).

5.1 | Crop resistance to pathogens

Genetic resistance to pathogens is one of the most important elements in non-chemical crop protection. It is usually divided into two types of host resistance (Poland & Rutkoski, 2016; Tronsmo et al., 2020; Van Der Plank, 1963):

- qualitative resistance (also known as race-specific, major gene, vertical, or *R* gene-mediated resistance), in which major *R* genes are very effective against some races of a pathogen

TABLE 4 Impacts of alternative crop and disease management on pathogen populations and environment

Management strategy	Impact on pathogens and/or environment	References
Resistance gene pyramiding (multiple resistance genes in one host cultivar)	Can reduce disease severity and improve durability of resistance	Lof and van der Werf (2017); Mundt (2018); REX Consortium (2016)
Cultivar mixture (cultivars with different resistant genes)	Can improve durability of resistance, decrease epidemic frequency and pathogen spread	Mikaberidze et al. (2015); Mundt (2002); Rimbaud et al. (2018, 2021); Wuest et al. (2021)
Intercropping	Can decrease number of susceptible hosts (dilution effect), change the microclimate inside the canopy compared to a monoculture, and decrease pathogen dispersal (barrier effect)	Boudreau (2013); Stomph et al. (2020)
Change canopy architecture	Can increase the canopy porosity, provide less favourable environment for pathogen, increase distance between susceptible host organs, improve fungicide/solution penetration to lower parts of canopy	Calonnec et al. (2013); Müller et al. (2018); Pangga et al. (2011); Tivoli et al. (2013)
No-till, crop residues left on field	Provides inoculum for following season, can produce more favourable environment for soilborne pathogens	Bockus and Shroyer (1998); Dill-Macky and Jones (2000); Kerdraon et al. (2019)
Crop rotation	Avoidance of host, break in the disease cycle	Bargués-Ribera and Gokhale (2020)
Biofumigation	Elimination of soilborne pathogens	van Bruggen et al. (2016); Matthiessen and Kirkegaard (2006); Morris et al. (2020)

- quantitative resistance (also known as race-nonspecific, minor gene, horizontal, or partial resistance), governed by several genes with minor effects on the pathogens.

However, the main challenge is to ensure the durability of these genetic resistances, as their effectiveness decreases with time due to the selection of virulent pathogen races/pathotypes (REX Consortium, 2016). McDonald and Linde (2002) developed a framework to identify which pathogens were the most likely to render crop resistance genes ineffective. They concluded that these pathogens were those with a mixed reproduction system (both sexual and asexual reproductive mechanisms), a high potential for genotype flow (movement of entire genotypes between distinct populations), large effective population sizes, and high mutation rates. For example, races of *P. striiformis* f. sp. *tritici*, the causal agent of wheat yellow rust, showed the potential to render major resistance genes ineffective and then spread across Europe (Bayles et al., 2000; Hovmøller et al., 2016). Moreover, quantitative resistance is perceived as more durable than qualitative resistance because partial resistance might involve less selection on pathogen populations and the different resistance genes involved might have different resistance mechanisms at different times during the growing season, which might then be more difficult for the pathogen to overcome (Mikaberidze et al., 2015; Pilet-Nayel et al., 2017).

There are different ways to deploy pathogen resistance in crops to increase its durability (Lof & van der Werf, 2017; REX Consortium, 2016):

- gene pyramiding: more than one resistance gene is present in a specific plant cultivar
- sequential use: when the resistance starts to be eroded, a new cultivar with a different resistance gene is substituted into the crop rotation
- simultaneous use (cultivar mixture): different cultivars with different resistance genes are used together in a crop.

Even if gene pyramiding is potentially more durable, it can be time-consuming to achieve in a breeding programme (Mundt, 2018; REX Consortium, 2016; Rimbaud et al., 2021). An easy way to quickly improve genetic diversity in a crop field is to use mixtures of cultivars with different resistance genes against different pathogen races (Garrett & Mundt, 1999; Mundt, 2002; Wuest et al., 2021). It is expected that host mixtures will reduce severity of disease epidemics by reducing the density of susceptible hosts, creating a barrier to the dispersal of pathogens, inducing resistance if plants are infected by an avirulent pathogen race, and increasing competition between pathogens or races of the same pathogen (Mikaberidze et al., 2015). In addition to a decrease in late potato blight (*P. infestans*) severity, Yang et al. (2019) observed other agronomic benefits, such as an increase in yield, greater stability of crop production and an increase in soil fertility, from growing a mixture of potato cultivars with different types of resistance against *P. infestans*. Recently, Pélissier et al. (2021) also showed plant–plant interactions ("Neighbour-Modulated Susceptibility to pathogen") in cultivar mixtures of rice and durum wheat; for both crops, they observed a modification in resistance gene expression primed by infected neighbour plants. Another important aspect of plant resistance is that susceptibility of the host or organ can vary with its development (Develey-Rivière & Galiana, 2007). Ontogenic or age-related resistance in ICM should be studied more (Jeger et al., 2021).

5.2 | Intercropping

Intercropping is defined as the simultaneous cultivation of two or more crop types during a growing season. In arable crop systems, intercrops usually involve mixing cereals with grain legumes to benefit the cereal from the nitrogen fixation by the legume (Maitra et al., 2021). This could then lead to a decrease in the use of N fertilizers and a reduction in ammonia emissions (Fung et al., 2019). Other benefits from cereal–grain legume intercrops by comparison with sole crops include increased yields, better yield stability, and improved protein concentration of the cereal grain (Bedoussac et al., 2015; Stomph et al., 2020). There are three different types of intercropping: (a) mixed intercropping when the crops are sown simultaneously, (b) relay intercropping when one crop is sown later than the other, and (c) row intercropping when two different crops are sown in alternating rows.

In an extended literature review of more than 200 studies comparing monocrops and intercrops, Boudreau (2013) noted that intercrops decreased crop disease development in 73% of the cases. Stomph et al. (2020) obtained a similar estimate of 78.6% of crop protection benefits from intercropping compared to a monocrop for 196 cases taken from 101 scientific papers, and intercropping increased disease incidence/severity in only 3.6% of the cases. The main beneficial effects to crop protection from intercropping are similar to those from cultivar mixtures, with a decrease in host density (dilution effect), physical barriers to pathogen spread (barrier effect), and a change in the canopy microclimate. Even if research papers usually focus on only one crop pathogen in intercropping systems, intercropping has the potential to protect against the pathogens of both crops at the same time. For example, in a wheat–pea intercrop, the dilution effect of nonhost plants on disease incidence/severity can be expected to apply to wheat yellow rust (Luo et al., 2021) and pea ascochyta blight, caused by *Didymella pinodes* (Schoeny et al., 2010). Two European Union's Horizon 2020 projects are currently in progress to fill the knowledge gap for intercropping: DIVERSify (https://plant-teams.org/) and ReMIX (https://www.remix-intercrops.eu/).

5.3 | Plant and crop canopy architecture

Altering crop canopy architecture can be another means to decrease the severity of crop disease epidemics whilst using less fungicides (Jeger et al., 2021). Plant architecture is defined by the topology and geometry of crop plant organs and changes with time during a growing season (Godin et al., 1999). By extension, canopy architecture represents the spatial distribution of the plants within a crop. Canopy architecture can be modified by different factors, such as cultivar characteristics (e.g., height, leaf shape), sowing date, and density, or mechanically by pruning or trimming to increase canopy porosity to maintain good aeration inside the canopy (Ando et al., 2007; Pangga et al., 2013; Tivoli et al., 2013). These modifications are made to enhance disease avoidance or slow down epidemic development by, for example, creating a less favourable microenvironment for the pathogen (Richard et al., 2013) or removing susceptible organs (McDonald et al., 2008).

Intercropping and cultivar mixtures are also a way to modify canopy architecture compared to a monocrop-cultivar canopy, providing a barrier to pathogen dispersal, a decrease in density of susceptible host tissues inside the canopy (i.e., an increase in the distance between susceptible tissues), and a less favourable microclimate for disease development (Calonnec et al., 2013). Compared to a monoculture, cultivars in a mixture can have different phenotypic characteristics (e.g., plant height, leaf size) that then decrease inoculum splash dispersal (Vidal et al., 2017). Changed canopy architecture can also improve effectiveness of fungicides and other plant protection products inside the canopy (Müller et al., 2018).

5.4 | Crop rotation

The aim of crop rotation is to sequentially grow different crop types in the same field by alternating susceptible and non-susceptible host crops to interrupt a disease cycle (Kirkegaard et al., 2008). This technique is more effective against soilborne pathogens than airborne pathogens (Tronsmo et al., 2020). Crop rotation can also help to improve or maintain soil quality by integrating cover crops (also referred to as green manure if they are integrated into the soil while still fresh and green) such as clover to improve soil nitrogen content in the sequence between cash crops (crops grown to provide a commercial product for sale) (Bargués-Ribera & Gokhale, 2020; Larkin, 2015). Crop rotation is commonly used to control take-all disease (*Gaeumannomyces graminis* var. *tritici*) of wheat (Cook, 2003). Larkin and Honeycutt (2006) studied the impact of different 3-year rotation sequences on incidence/severity of stem and stolon canker and black scurf of potato (caused by *Rhizoctonia solani*) compared to growing potato continuously. There was a decrease in incidence/severity of diseases for most rotation combinations, but some rotation sequences resulted in some disease problems. Andert et al. (2016) observed the importance of carefully selecting the crops in the rotation sequence, with sometimes a greater need for fungicide application than in continuous cultivation of the same crop. The frequency of the host crop in the rotation was also an important factor and might require more than one growing season without the host for it to be more effective (Bailey & Lazarovits, 2003; Hegewald et al., 2018). There is also a risk for the cover crop to be a "green bridge" or reservoir for pests and pathogens for the following cash crop and then should be carefully selected to avoid alternative hosts in the rotation. For example, Bakker et al. (2016) identified potential pathogens against maize as a cash crop in winter rye used as a cover crop the previous season.

Another aspect of the role of cover crops for crop protection is use for biofumigation against soil pests and pathogens (Panth et al., 2020; Rosskopf et al., 2020). Biofumigation is the incorporation into the soil of fresh plant tissues from the Brassicaceae family that are high in glucosinolate-content (Matthiessen & Kirkegaard, 2006) in order to replace synthetic fumigants (e.g., methyl bromide). Morris et al. (2020) reviewed 46 publications representing 934 experiments and noted that generally biofumigation reduced disease incidence and pest abundance and increased crop yield compared to untreated controls, but the size of the effect was very dependent on the pathogen, host, and cover crop species.

5.5 | Other alternative methods

Even if these crop protection techniques provide some effective protection against some pathogens, they will benefit from more breeding work to reach their full potential, because currently breeding programmes are more focused on high-density monocrops (Boudreau, 2013; Chen et al., 2021; Jeger et al., 2021). Another approach is to combine these techniques to increase their effects on crop diseases. Other management techniques might be developed or deployed in the future. For example, biological control involves the use of living organisms against plant pathogens to either induce plant host resistance or compete with the target pathogens for resource allocation (Köhl et al., 2019). Amongst 113 fungal genera, Thambugala et al. (2020) identified some *Trichoderma* species as antagonistic fungal species with the greatest potential as biocontrol agents against fungal plant pathogens. Another method that might be deployed to manage soilborne pathogens, given the increase in temperature due to climate change in southern Europe, is soil solarization (Juroszek & von Tiedemann, 2011; Panth et al., 2020). Soil solarization, involving covering moist soil with a layer of transparent plastic, is being used in organic farms in Israel and the United States (van Bruggen et al., 2016).

6 | MANAGEMENT PRACTICES THAT CAN HAVE AN INDIRECT IMPACT ON CROP PATHOGENS

Alternative farming systems can have indirect impacts on crop pathogens. One of the benefits of conventional tillage is to bury and degrade crop residues, destroying potential primary inoculum that can initiate disease epidemics in the following growing season (Hofgaard et al., 2016; Ogle & Dale, 1997). In no-till systems with crop residues left on field surfaces as mulch to limit soil erosion (e.g., in conservation agriculture), these residues can provide airborne pathogen inoculum for starting epidemics in the following growing season

(Dill-Macky & Jones, 2000; Kerdraon et al., 2019). The residues can also increase humidity at the soil surface, which can then improve overwintering survival of the pathogen (Bockus & Shroyer, 1998; Giller et al., 2015). However, if there is a crop rotation with a nonhost crop planted in the following growing season, the inoculum from the residues will not produce an epidemic if there is no susceptible host crop in nearby fields (Bailey & Lazarovits, 2003; Flower et al., 2021; Schroeder & Paulitz, 2006).

Another management practice in low-input systems that can lead to an increase in crop diseases is low fertilization. Low concentrations of N and K can weaken plant defences against pathogens and thus increase disease severity (Dordas, 2008; Ghorbani et al., 2009). However, excess N can also increase disease severity, especially for diseases caused by obligate biotrophic pathogens (Dordas, 2008; Veresoglou et al., 2013), as a result of an increased leaf N-content or denser canopy, for example (Walters & Bingham, 2007). Hence, less severe wheat yellow rust epidemics were often observed in organic than in conventional farming systems due to the lower N concentrations in organic wheat tissues (van Bruggen & Finckh, 2016). In a 2-year field experiment with four different N fertilizer rates (0, 90, 180, and 270 kg/ha), Luo et al. (2021) observed that increasing N concentration increased incidence and severity of wheat powdery mildew (*Blumeria graminis* f. sp. *tritici*) and yellow rust. In addition, the form of the N fertilizer (either as ammonium NH_4^+ or nitrate NO_3^-) can also increase or decrease disease severity (Sun et al., 2020), possibly due to a change in soil pH associated with the different fertilizer forms (Agrios, 2005; Ghorbani et al., 2009).

Organic soil amendments (e.g., manure or compost) are also used to improve soil health by increasing soil organic carbon content and can have direct or indirect effects on soilborne pathogens (Jayaraman et al., 2021; Larkin, 2015; Vida et al., 2020; Walters & Bingham, 2007). Bonanomi et al. (2007) analysed 250 studies involving organic matter amendments and observed a significant suppressive effect in 45% of the cases (with compost the most effective amendment and peat the least effective); there was no significant effect in 35% of the cases, and an increase in disease in 20% of cases. These suppressive soils act in the same way as biocontrol agents by stimulating antagonistic indigenous microorganisms operating against soilborne pathogens by means of direct antagonism, antibiosis, parasitism, or competition for resource acquisition (Bonanomi et al., 2018; Panth et al., 2020; Schlatter et al., 2017). However, these characteristics are usually not transferable from one soil to another.

Irrigation can be a means of pathogen dispersal; for example, splashing or washing down of foliar pathogens may be favoured by overhead irrigation, and low-level (flooding) irrigation may favour soilborne pathogens or contaminate the water supply (Agrios, 2005; Dixon, 2015; Hong & Moorman, 2005). With climate change, it is expected that water scarcity will increase, including in southern Europe (Table 2). Farming systems will then need to evolve to low-input use of water, better irrigation management, breeding for crops with drought tolerance and better water-use efficiency. A recent review by Swett (2020) showed that there is little information about this effect on arable crop pathogens. Swett noted that changing to a drip irrigation system can help to control both foliar and soilborne pathogens but reducing amounts of water can also induce plant water stress and then weaken plant defences against pathogens. The amount of water provided by the irrigation system should also be carefully planned to avoid increased relative humidity in the crop canopy or soil wetness, which could then favour the pathogen development, especially under dense canopies, which tend to dry out slowly (Pangga et al., 2011).

7 | APPLICATIONS OF ADVANCED INFORMATION AND COMMUNICATION TECHNOLOGIES IN CROP PROTECTION

Digital tools can be used to improve ICM practices. As monitoring technology and computer power are increasing, these tools are constantly improving in their robustness and precision.

7.1 | Precision agriculture

Precision agriculture considers within-field crop variability to manage and apply fertilizer or pesticides only to parts of the field where they are needed during the growing season. By extension, precision crop protection aims to optimize disease management by focusing only on those areas within a field where a disease is detected by remote sensing, avoiding excessive and expensive use of crop protection products (Mahlein et al., 2018). Different types of non-invasive sensors can be used to detect a change in crop health, identify the disease, and quantify the severity of the symptoms (phytopathometry) to inform the farmer where it is necessary to apply a treatment within a crop (Mahlein, 2016; Oerke, 2020; West et al., 2003; Yang, 2020). Optical sensors may use red-green-blue (RGB) imaging (i.e., digital photography), multispectral sensors (usually cameras combining RGB and near-infrared wavelengths) or hyperspectral reflectance sensors (with more narrow wavelength measurements in a continuous wider spectrum), thermal sensors (to assess plant temperature), or chlorophyll-fluorescence sensors (to estimate differences in the photosynthetic activity of plants). These sensors can be used on satellites, unmanned airborne vehicles (UAV), or drones. In addition, electronic noses can be deployed to detect volatile organic compounds emitted by plants attacked by a pathogen (Oerke, 2020; Silva et al., 2021).

One of the main challenges for this technology is to be able to detect the early onset of a disease to keep the treatment as localized as possible and minimize the amount of crop protection product used, ideally during the latent periods of pathogens before the appearance of visible symptoms (Lowe et al., 2017). At the moment, remote sensing sensors are better adapted for local soilborne pathogens than for fast-spreading airborne pathogens (Yang, 2020). Ideally, optical sensors will provide site-specific geographic distribution maps of the pathogen within a crop to guide local spraying of plant protection products (Mahlein, 2016; West et al., 2003). To achieve this, another technological challenge is how to rapidly analyse and interpret the large amount of data generated by remote sensing (Mahlein, 2016; Oerke, 2020). Machine learning and deep learning methods will be needed to resolve this (Mahlein et al., 2018; Oerke, 2020).

7.2 | Forecasting

Computer models can be powerful tools to guide control of crop pathogens by forecasting risks of severe crop disease epidemics (Rossi et al., 2019). These models can be “simple” models based on weather parameters to predict infection risks (Magarey et al., 2005) or more complex mechanistic compartmental models (with different submodules to model stages in a pathogen life cycle) to simulate changes in disease severity and epidemic development in a host population during a growing season (De Wolf & Isard, 2007; Gilligan & van den Bosch, 2008).

One challenge for estimation of yield loss is how to combine these epidemiological models with process-based crop growth models (Bregaglio et al., 2021; Cunniffe et al., 2015; Donatelli et al., 2017). To respect ICM principles, there is a need to develop decision support systems (DSS) with economic thresholds to estimate when it is economically feasible to apply crop protection products with a limited impact on the environment (Gilligan, 2008). These DSS could then help to reduce plant protection product applications whilst decreasing disease incidence/severity (Shtienberg, 2013). However, forecasting models can predict when spores are released or estimate optimal conditions for infection but cannot guarantee that a pathogen is present. Automatic spore samplers could be a good solution to complement these systems (Oerke, 2020) but there is a lack of knowledge about the scale/resolution at which a network of samplers should be deployed (Jackson & Bayliss, 2011; Van der Heyden et al., 2021; West & Kimber, 2015).

8 | POTENTIAL PROGRESS AND FUTURE RESEARCH NEEDS

All these techniques (Table 4) are continuously improving but not widely used in Europe, except for crop genetic resistance. A survey of European experts by Lamichhane et al. (2018) regarding implementation of ICM techniques concluded that farmers are interested to develop them in conventional, organic, or low-input farming systems. However, data are still lacking to guide economic decisions by farmers. These techniques will need to rely more on ecosystem services and agroecology (Barrios et al., 2020; Wezel et al., 2020) to help mitigate and adapt to climate change and contribute to the European Union “Farm-to-Fork” strategy (https://ec.europa.eu/food/horizontal-topics/farm-fork-strategy_en).

8.1 | Potential reduction in GHG emissions with alternative or conventional agriculture

It is expected that use of these systems that are alternative to conventional agriculture will help to reduce or replace the use of synthetic chemical inputs. It is also hoped that they will help to reduce GHG emissions, with less emissions from the use of environmentally friendly plant protection products, less machinery used in crops, less fertilizer and plant protection product residues leaching to water streams, and less soil disruption. This improvement in environmental health is one of the key components to integrate plant protection in the One Health concept. However, it is difficult to precisely estimate the secondary benefits from use of fewer synthetic fungicides. Some studies used life cycle analysis to do so (Tubiello et al., 2021). At the moment, crop protection product applications in conventional agricultural systems produce greater yields on less land and have a better nitrogen use efficiency than in low-input systems, resulting in less GHG emissions, despite production and application emissions (Hughes et al., 2011). Low-input systems then need to achieve similar levels of crop production and crop protection per hectare to conventional agricultural systems to produce less GHG (Carlton et al., 2012). This has been a research topic between the use of land-sharing and land-sparing tactics to combat food security and environmental impacts under climate change (Fischer et al., 2014). However, these authors observed that reducing tillage in conventional farming systems is a first step to reducing GHG emissions. Furthermore, cultivars that are resistant to pathogens require fewer fungicide applications than susceptible cultivars and this can also help to reduce GHG emissions (Mahmuti et al., 2009). Thus, organic agriculture might not be such a good option at the moment because it produces less yield per hectare than conventional agriculture (Clark, 2020) and consequently releases more GHG (Röös et al., 2018). Smith et al. (2019) predicted that converting all food production in England and Wales to organic systems would lead to a net increase in GHG due to the need to import more food from overseas to compensate for the shortfalls in local food production and an increase in N_2O emissions due to greater leaching and denitrification from organic manures. In a comparison of meta-analyses of 5156 experiments on techniques to increase crop diversification (including crop rotation, cultivar mixtures, and intercropping), Beillouin et al. (2021) observed that despite their potential to limit crop pests and pathogens, these techniques could produce more emissions of GHG (e.g., N_2O emission from legume cover crops) than conventional farming. However, they also identified some gaps and uncertainties, such as a decrease in nitrogen leaching, which might counterbalance this negative effect. More life cycle analysis studies are needed to assess the full GHG emissions linked to ecosystem services and use of less machinery in low-input systems compared to conventional agricultural systems.

8.2 | Crop health management at landscape/regional scales

One way to improve ICM is to organize disease management at the landscape scale to decrease the size of pathogen inoculum sources and inoculum concentrations (Figure 5). To study the dynamics of disease spread at the landscape scale is more complex than at the

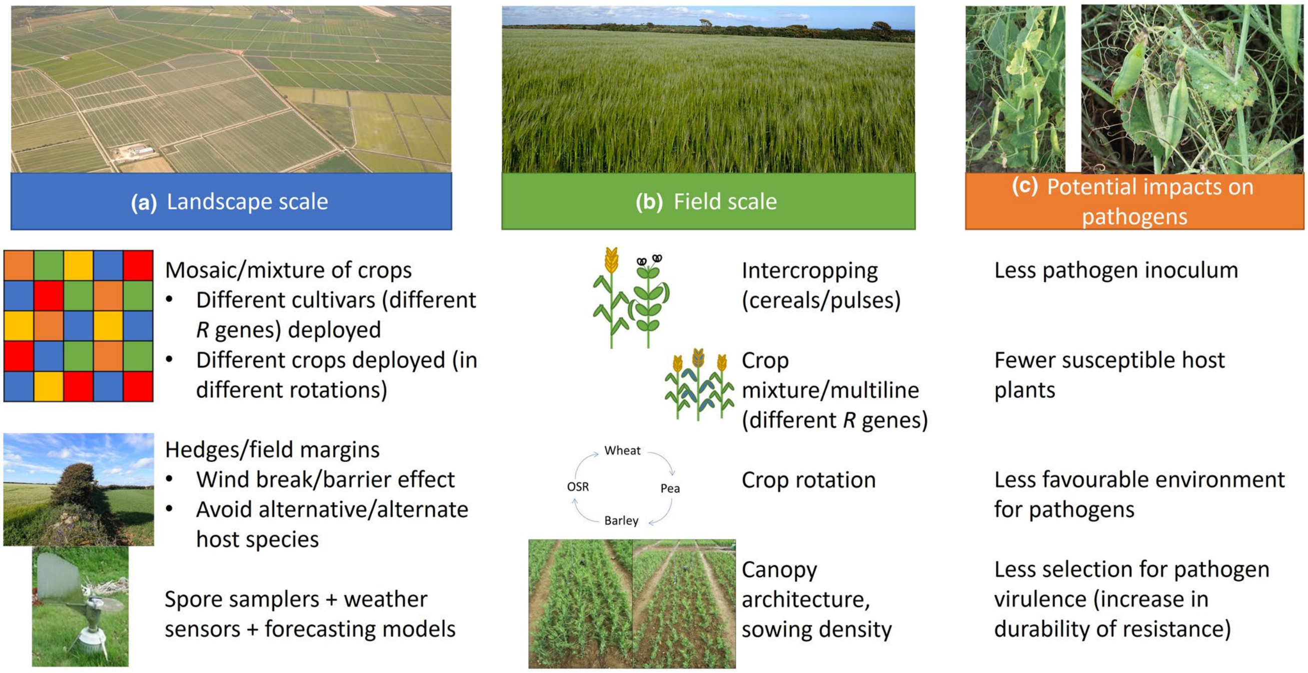

FIGURE 5 Examples of Integrated Crop Management strategies to decrease severity of arable crop diseases at a landscape scale (a) or a crop field scale (b) in relation to their potential impacts on crop pathogen population dynamics (c)

field scale, as it depends on the arrangement of host crop fields within the landscape and the dispersal dynamics of the pathogen (Fabre et al., 2021; Gilligan, 2008). The landscape can then be considered as a mosaic of various crops, and studies were done using computer simulations to identify the best strategies for deployment of resistant cultivars to ensure durability of resistance (Papaïx et al., 2018; Rimbaud et al., 2018). Rimbaud et al. (2021) compared different models for deployment of resistance at the landscape scale and observed that, even though the models were not developed to be compared, enhancing diversity of resistance at the landscape scale with crop rotation and use of different resistance genes in different fields can impede pathogen evolution to virulence. However, they suggested that more data are needed because there could be limitations to the feasibility and economic viability for farmers to deploy these strategies.

Hedgerows can be used as windbreaks between fields and therefore decrease pathogen dispersal between crops (Beillouin et al., 2021; Ogle & Dale, 1997; Plantegenest et al., 2007), even though hedgerows are usually studied as a means to reduce pesticide drift from a field (Ucar & Hall, 2001). However, the species used as hedgerows should be carefully selected so that hedgerows do not become reservoirs for pathogens if they include species that can be alternative hosts (on which the pathogen can develop) or alternate hosts (needed by the pathogen to complete its life cycle). One example is to avoid planting barberry bushes near cereal fields, because barberry is an alternate host of the wheat stem rust pathogen *P. graminis* f. sp. *tritici* (Zhan et al., 2015). Moreover, tree hedgerows can also increase the water stress of the nearby crops and then increase disease severity on them (Smiley & Machado, 2020).

8.3 | Monitor, detect, and protect

Combining disease forecasting models with regional spore inoculum data and weather data from a weather station network can provide a robust and reliable DSS (Newlands, 2018; Yuen & Mila, 2015). However, it is important for disease forecasting and precision agriculture to quickly detect the presence of a pathogen, or at least to know if a pathogen was recently detected in an area. As airborne pathogens can travel long distances (Meyer et al., 2017), international surveillance networks are important to determine whether or not a specific pathogen or specific pathogen race is present in an area. For example, the European "RustWatch" network (https://agro.au.dk/forskning/projekter/rustwatch/) monitors races of wheat yellow rust, leaf rust, and stem rust pathogens. The European and Mediterranean Plant Protection Organization (EPPO) and the European Food Safety Authority (EFSA) provide databases and information about diseases and pests in Europe, including first reports of newly detected pathogens in each country. Citizen science programmes, also called passive surveillance programmes, are programmes that involve members of the public participating in the detection of a pathogen or host; the relevant authorities can then be informed if the pathogen/host is encountered and this information can then be used to develop crop protection surveillance networks (Brown et al., 2020). For example, the Barbery Rust Explorer ("BarbRE," https://barbre.co.uk/) project coordinated by the John Innes Centre aims to track common barberry (alternate host for wheat stem and yellow rusts) distribution in the United Kingdom to ultimately estimate the potential risk that these pathogens can complete their life cycles in the United Kingdom.

8.4 | Use of new technologies for ICM breeding

Technologies are always evolving, and some technologies that will be used in 10 years' time are not available yet. In addition to classic resistance breeding programmes, new technologies such as genome editing could be used to accelerate them. CRISPR/Cas9 technology can be used to knock-out major susceptibility genes and negative regulators of host defence pathways to improve resistance of crop plants against pathogens more easily than at present (Gosavi et al., 2020; Langner et al., 2018). Genomic selection, which employs statistical whole-genome models using genome-wide molecular markers to predict unobserved individuals to improve plant breeding cycles (Crossa et al., 2017), could be applied to host resistance breeding (Poland & Rutkoski, 2016). Ultimately, it is expected that a new generation of models combining crop growth models with parameters based on genomic prediction will be used to predict genotype × environment × management interactions (Bustos-Korts et al., 2019; Hammer et al., 2019) and potentially combine with disease models to virtually develop ideotypes and ICM strategies.

There is also a constant improvement in computer hardware (Noll & Henkel, 2020) and it is now possible to run more complex models in less time than previously. However, to do this, it is necessary to process large amounts of data (Rimbaud et al., 2021). Often, research papers focus on one crop and one pathogen, which does not help to develop ICM at the field or landscape scale, where more than one pathogen (and crop) is usually present. There is then a need to do more interdisciplinary experiments at the landscape scale with different levels of resolution and to share the results. A "Rosetta stone" will be needed to facilitate communication and knowledge transfer between modellers, geneticists, epidemiologists, stakeholders, and farmers for the development of fit-for-purpose ICM (Silva et al., 2021).

8.5 | Control of crop commodity trade

The pandemic outbreak of COVID-19 has slowed down/prevented free passenger travel in the past two years. However, in a changing world where international travel is still expected to increase, there are increased risks of spread of new pathogens and new pathogen races to new areas, through food imports (including in the packaging) or by tourists, such as soybean rust (*Phakopsora pachyrhizi*) or wheat blast (*Pyricularia oryzae* pathotype Triticum) (Fones et al., 2020). During the recent International Year of Plant Health, there was an increase in communication to the public about the risks of importing new pathogens into a country. The EPPO campaign "Don't risk it" is in place in many airports to inform international travellers not to bring back plants or seeds that might carry (exotic) pathogens.

8.6 | Knowledge transfer and collaboration

One important method to achieve strategies like this is by knowledge transfer. There is a need to improve transfer of research project outputs to a wider community of experts and stakeholders. One new way to do so is to develop serious games such as "SEGAE" (Jouan et al., 2021), which was used to teach agroecology from the Erasmus+SEGAE project, and "Interplay" (http://vm193-134.its.uni-kassel.de/En. DiversiWiki/index.php/Serious_Game) based on intercropping results from the ReMIX project (https://www.remix-intercrops.eu/Home/Latest-News/INTERPLAY-serious-game-released). With the COVID-19 pandemic, which has impeded knowledge transfer through meetings, initiatives such as "Open Plant Pathology" (https://openplantpathology.org/) are welcomed to maintain and encourage communication between scientists.

9 | CONCLUSIONS

Agricultural systems have gone from man-powered to horse-powered, then to the present intensive machine-powered stages in Europe. The future move is being striven towards data-driven crop production and management systems with applications of advanced technologies such as genome-editing techniques, robots, global positioning system (GPS), UAV and satellite-derived images. Despite providing high yields per hectare, the present intensive conventional agriculture has been recognized as an important source of GHG and produces many unintended negative impacts on the environment in the long term, for example, water pollution with nitrate and pesticide residues leaching. Efforts are needed to change to more sustainable ways of crop production, relying less on synthetic inputs for fertilization and crop protection and less on fossil fuel-powered machinery. One of the main challenges of the 21st century is then to achieve this whilst increasing crop yields per hectare to feed a current large and increasing world population and tackling climate change. On the other hand, organic farming and conservation agriculture produce lower yield per hectare and can currently generate more GHG emissions per unit of yield than conventional agriculture. Promising ICM solutions are being developed and will need to be locally adapted at the landscape scale to be more effective. These methods usually have more of a prophylactic effect on crop diseases by creating environments that do not favour pathogen development, removing susceptible hosts or residues, or increasing host resistance against the pathogen rather than killing it with a fungicide application. However, to maintain and increase yields and assure food security and safety in the short term, farming practices will still need to rely on use of synthetic products. Of particular importance are uses of new fungicides that are target-specific with novel modes of action and high efficacy at low doses, leaving no or less residue on the harvested products. As a consequence of advances in modern technology and digital tools, it should be possible to decrease their use to achieve more environmentally friendly disease control. The use of pathogen-resistant cultivars in crop production is currently the most economical and effective way to reduce losses caused by diseases, as well as the most studied approach. However, this requires the development of effective and durable pathogen-resistant crop cultivars to control increasingly serious diseases caused by both existing and emerging new pathogens in the future changing climate. More breeding efforts are needed to test performance of cultivars in intercropping and cultivar mixtures instead of as monocrops. Field experiment data on combinations of these ICM strategies in different environments are also needed to find the best solutions to deploy them in terms not only of crop protection, but also of decreasing GHG emissions and other ecosystem services such as increasing biodiversity and soil carbon sequestration potential, to integrate them in the "One Health" approach. To guarantee the best interpretation and use of these interdisciplinary data sets, it is essential to ensure an open access to them with a clear description of them.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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