Success and challenges of crop protection

Agrow's guest author, Dr Piet Boonekamp, provides a comprehensive view of crop protection from its origins to future directions and IPM

Since the beginning of agriculture with the domestication of plants around 10,000 years ago, wild species were collected and continually selected for better growth, higher yield and better quality of consumable products. Focusing solely on these quality traits was automatically associated with a reduction in the ability of crops to withstand pests and diseases. That led to the dawn of the crop protection era as people tried to reduce crop damage. Some records indicate that the Chinese used sulfur compounds in 2000 BC to keep crops healthy. In the European Charlemagne era (around 800 AD), crop rotation was recorded. Due to the network of knowledgeable monasteries, that continued to grow over Europe until around 1400 AD.

No new advances occurred over the next few centuries partly because of the general belief that bad symptoms in plants were not caused by diseases but were the consequence of unhealthy growing conditions. This idea continued until the 19th century with the result that people initially did not accept evidence that bunt of wheat and potato blight where caused by fungi. The end of the 19th century, when it was found that copper sulfate and lime (Bordeaux mixture) were effective against downy mildew of grapevines, can be considered as the start of modern crop protection. For the first time the concept of plant diseases as causative agents and their treatment were accepted.

So modern crop protection is a little over 100 years old, but has developed rapidly. During the period 1900–1940, the scientific disciplines of virology, mycology, bacteriology, entomology and nematology evolved and plant diseases were linked to various causative organisms. But crop protection measures did not evolve rapidly and were still based on inorganic copper, sulfur and mercury mixtures. During 1940–1970, and especially after the Second World War, food production and food security became a high political priority in the Western world. Chemical and oil companies moved into agriculture with the development and production of organic crop protection compounds. A large number of organic compounds were developed and used for crop protection during this period (Russell 2005), and some are still used today. In the 1960s and 1970s, people became aware of the negative side effects of pesticides, fuelled by the book “Silent Spring” (1962), the report “The Limits to Growth: A Report to The Club of Rome” (1972), and the devastating effects of Agent Orange during the Vietnam War. As a result, stricter regulation of pesticides was introduced.

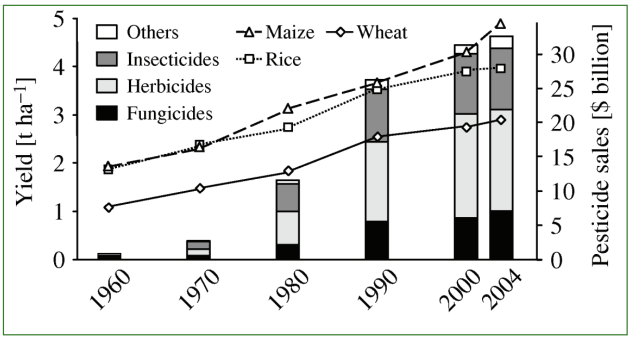


Fig. 1 Development of the worldwide average yield per unit of area for wheat, rice and maize and pesticide sales in the period 1960–2004 (from Oerke 2006)

From the 1970s onwards, modern crop protection products have been highly science-based, well characterised, extensively tested for specificity and toxic effects on non-target organisms and human health, and strictly regulated by public authorities. The consequence is that the costs to a company from development to application are now extremely high for a product, which has led to company mergers, fewer compounds with new modes of action, and renewal of compounds for the major crops only, as such markets are large enough to secure economic profits.

impact of chemical crop protection

After the Second World War, the Western agricultural policy was “more with more” – more production of food, that could only be realised with more input/output per ha, as fertile arable land could not be expanded. Asia and South America followed a bit later with the “Green Revolution”. Combined with breeding for new varieties, and chemical fertilisers, effective crop protection was responsible for more than doubling the productivity of the main food crops (Figure 1, Oerke 2006). The increased food production could match the more than doubling of the world population during the last 50 years, securing in principle enough food for everybody, but unequal distribution still causes food shortage in many parts of the world. However, the amount of applied pesticides increased much more (15-fold) and residues in the environment became a problem. The industry acted by setting up decision support systems to advise farmers to spray at recommended doses. In addition, biocontrol alternatives, developed in the 1970s by academic research, were brought onto the market by new, small companies. Recently, major chemical crop protection companies have taken initiatives to add biopesticides to their crop protection portfolios. As most

of these developments were outside the original chemical core expertise of the companies, collaborations with public research organisations and universities were started in large Public-Private-Partnership (PPP) programmes.

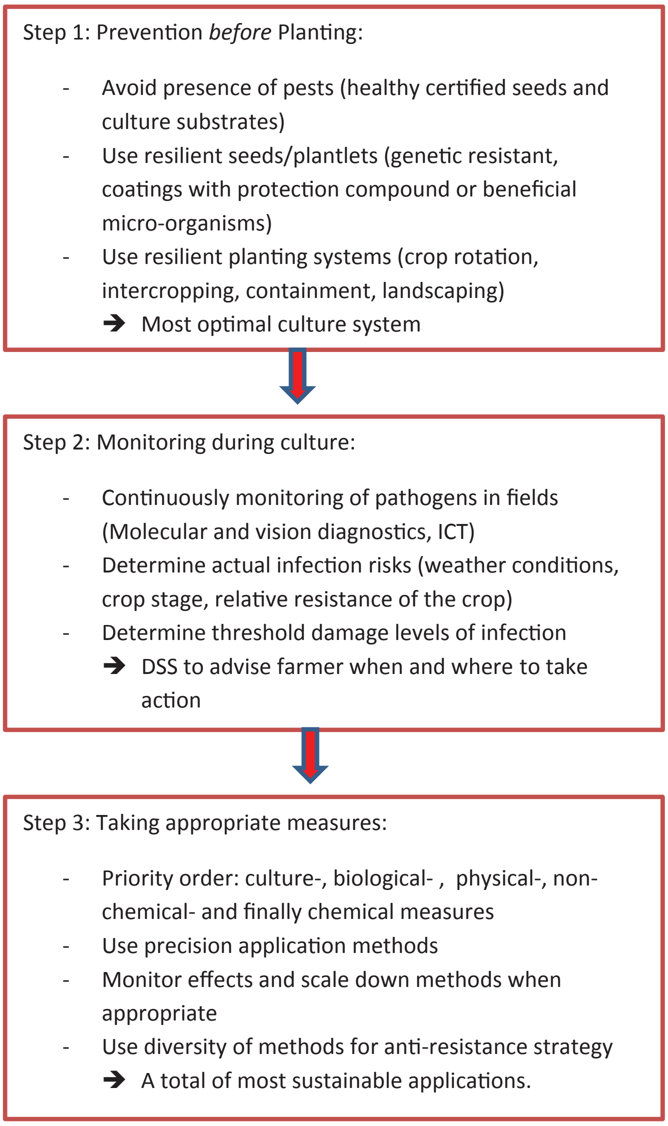
the challenge for the coming decades

The world population is forecast to increase to 9 billion by 2040. Food production has to change to obtain "more with less" – doubling of the production on less land, and with less input of fertilisers and pesticides to meet sustainability goals. The availability of fewer new chemical products might lead to rapid resistance of pathogens and crop protection needs to diversify. In addition, pathogens might spread more easily over the planet through international trade. It is also anticipated that climate change will lead to more, and not easily predicted, disease outbreaks and development of pathogens with new epidemiological characteristics, no longer matching present control systems (Boonekamp 2012). Resilient cropping and crop protection systems have to be developed to cope with strongly fluctuating biological and physical stresses on crops. For crop protection, an important first step is further development of IPM.

The EU took the lead through Directive 2009/128 with a focus on IPM measures. Each member state had to comply with the Directive by submitting a National Action Plan in 2012 with concrete steps on how to develop and implement IPM principles during the next decade, being effective by 2023. The Directive is precise on the definition of IPM and farmers need to take eight principles into account for proper crop protection planning. The principles can be grouped into three steps: prevention before planting; monitoring during culture; and taking appropriate measures (see Figure 2).

a role for public-private research

Although aspects of every step of IPM can be implemented at present, biological knowledge and tools are too limited to optimise IPM systems for all crops and cropping systems. The required breakthroughs in IPM development during the coming decade depend highly on biological knowledge of plant-pathogen-environment interactions, on new principles of precision monitoring, and on sustainable integrated measures.



Step 1: Prevention *before* Planting:

- Avoid presence of pests (healthy certified seeds and culture substrates)
- Use resilient seeds/plantlets (genetic resistant, coatings with protection compound or beneficial micro-organisms)
- Use resilient planting systems (crop rotation, intercropping, containment, landscaping)

➔ Most optimal culture system

Step 2: Monitoring during culture:

- Continuously monitoring of pathogens in fields (Molecular and vision diagnostics, ICT)
- Determine actual infection risks (weather conditions, crop stage, relative resistance of the crop)
- Determine threshold damage levels of infection

➔ DSS to advise farmer when and where to take action

Step 3: Taking appropriate measures:

- Priority order: culture-, biological- , physical-, non-chemical- and finally chemical measures
- Use precision application methods
- Monitor effects and scale down methods when appropriate
- Use diversity of methods for anti-resistance strategy

➔ A total of most sustainable applications.

Fig. 2 Practical definition of IPM according to the EU Directive 2009/128/EC in steps to be taken before (step 1) and after (step 2 and 3) planting by the farmer

For step 1 (prevention), a long-lasting public-private collaboration already exists in the field of diagnostics (assays developed by public research and applied to certify millions of seeds, plantlets and other starting materials), resistance breeding (new genes and technologies) and cropping systems (greenhouses, optimisation of culture substrates, soil health and landscaping). A challenging new field is seed coating with beneficial micro-organisms. Including beneficial micro-organisms in the seed coatings that colonise the rhizosphere after emergence could support plant health by increasing uptake of essential nutrients and prevention of infections by soil-borne pathogens. Although straight-forward as a concept, and technically feasible as shown by Bennett et al (2009) who were able to apply high concentrations of beneficial micro-organisms on carrot and onion seeds by a commercial priming process, the positive effects in field trials on emergence of plantlets and disease suppression are not easy to maintain in practice. More public-private research is needed to establish robust coated seed systems.

For step 2 (monitoring), quantitative monitoring of spores during the season is already possible. For example, for *Phytophthora infestans* in potatoes, such monitoring is used for an advanced decision support system in practice, supported by industry. As multiple resistance is becoming available by pyramiding resistance genes in one potato clone using cisgenesis technology (Haverkort et al 2008), limited crop protection sprays will be needed when current potato crops harbour these multiple genes and if proper resistance management is executed. The latter is essential as *Phytophthora* spp is known to be very flexible in its virulence genes, easily forming new isolates that "break" resistance genes in the potato. To avoid this, such *P infestans* isolates with new virulence genes should be monitored during the growth season, and destroyed immediately when they are formed, as they have a great selective advantage over the other isolates that cannot propagate on resistant potatoes. A monitoring assay for one virulence gene has been developed and successfully tested in the field (our unpublished data). If multiple resistance of potato is applied in practice in combination with the new virulence monitoring, sustainable chemical control, and sustainable use of precious resistance genes is anticipated.

For step 3 (measures), a further public-private collaboration might lead to increased possibilities of biocontrol. The challenge is to obtain the right biocontrol organisms from the enormous diversity of organisms that are present in nature, and are linked to plants in the phylosphere and rhizosphere, containing unknown species with biocontrol potential. Until now, biocontrol products from only limited species have been developed because most screening programmes start immediately with a focus on efficacy, without taking other important factors into account (Kohl et al 2011). This means that many collections present in academia and collection centres can be tapped for promising genera and species of micro-organisms, outside the presently used biodiversity. This might lead to new biocontrol agents with completely different modes of action.

new crop protection concepts: a major challenge for science

The domestication of plants for higher food production automatically made plants more sensitive to pests and disease attack. The rapid increase of biological knowledge of plant development and internal signalling mechanisms in relation to its biological and physical environment based on genomics, proteomics and metabolomics, and knowledge of the interaction with biotic and abiotic signals from outside, may enable the design of culture plants with high production and low disease sensitivity.

The first building block is focusing on a different kind of resistance. Presently all resistance breeding by classical methods and genetic modification focuses on dominant major resistance genes (R-genes). These R-genes produce proteins that very specifically recognise so-called effector proteins from the infecting pathogen and this interaction leads to a resistance response of the plant. If the pathogen changes its effector, it will be no longer be recognised and infection occurs. Due to the large genetic dynamics of most pathogens and the large variety of effector genes, this occurs regularly. Two new mechanisms of resistance have recently been found. The first is exploring the use of susceptibility genes (S-genes) instead of R-genes. S-genes encode for factors needed for suppression of internal defence or as targets to support successful infection (Pavan et al 2010). Loss-of-function mutation of an S-gene leads to a recessive resistance. The challenge is to locate these S-genes in crops and to develop methods to make loss-of-function mutants of these genes for resistance breeding.

Another approach is making use of non-host resistance (NHR), a widespread phenomenon where some plants completely and continuously resist pests and diseases that are successful in infection of other plants. In Arabidopsis, a large panel of genes has been found for pre- and post-invasive blocking of a large variety of non-adapted pathogens. Some are related to so-called innate immunity, which can be activated by general pathogen-associated molecular patterns (PAMPs) or even by microbe-associated molecular patterns (MAMPs), not associated with pathogens, and even by compounds derived from tissue damage (Fan and Doerner 2012). The combination of gene activities ensures that a large number of pathogens will never be successful in infection. Orthologs of Arabidopsis genes have been discovered recently in crops and knowledge on the function, mechanism of action towards pathogens, and modes for activation of these genes is necessary before they can be exploited. And finally, among all the new technologies still under the genetic modification regulation, the recent RNA interference (RNAi) technology might be very promising to obtain precise and flexible resistance in plants to specific pests and pathogens (Kupferschmidt 2013).

A second building block is formed of endophytes, micro-organisms living inside plants being non-pathogenic, but having a symbiotic/mutualistic relationship with the plant functions. Many viruses, bacteria and fungi can be endophytic in all parts and during all life-cycles of the plant. Virus studies are relatively new and it is anticipated that more persistent endophytic, non-pathogenic virus species are present in wild and also in cultured plants, than pathogenic ones. Very recently, some clear mutualistic functions have been discovered, such as the induction of cold and drought tolerance in the host plant, but any effects on infectious pathogens of plants have still to be discovered (Roossinck 2013). Most known endophytic bacteria belonging to the Pseudomonas, Bacillus, Agrobacterium and Serratia genera, originate from the rhizosphere. They are able to enter the plant roots and are transported upwards into the plant tissues. They might contribute to resistance to various diseases as recently reported for the effect of Serratia on the black leg causing *Dickeya* spp in potatoes (Czajkowski et al 2012), but conclusive practical effects depend on efficient colonisation in the plant, a process that is still poorly understood. For endophytic fungi, the situation seems more complicated. Although they comprise diverse taxonomic groups, the consensus is that endophytic fungi can be either pathogenic, depending on the host and circumstances, or non-pathogenic having a mutualistic relationship with the host plant which benefits in terms of resistance to various stresses. Strains have been selected and widely applied, that only produce alkaloids against insects and not the alkaloid compounds that have adverse effects on grazing cattle (Thom et al 2012).

A third building block is the microbiome in the rhizosphere, the narrow zone of soil around roots, influenced by secreted plant signals. The rhizosphere can contain more than 1011 microbial cells per gramme of root, with more than 30,000 prokaryotic species (Berendsen et al 2012). The microbial population densities in the rhizosphere are much higher than in the surrounding soil, less diverse, and highly influenced by the plant roots. Every plant determines the composition of its own rhizosphere community, leading to a finger-print like microbiome. The microbiome might suppress soil-borne diseases effectively by antagonism or by producing inhibiting antibiotics. The microbiome can also indirectly prevent diseases by attracting beneficial microbes from the soil into the microbiome, and by a systemic mode of action by stimulating the innate immunity mechanism in other plant parts, leading to a broader suppression of diseases.

Focus on IPM during the next decade is expected to lead to an effective, more diversified and sustainable crop protection system. The fundamental problem is that crops, due to their requirement in good quality and quantity for food, will always be highly dependent on crop protection. The great challenge of the 21st century is to keep crops with the highest food value, but giving them back traits for disease-insensitivity, that have been lost during the domestication that started 10,000 years ago. Exciting new science will contribute to the development of new generations of resilient crops and cropping systems.

♦ *Dr Piet Boonekamp is the manager of the business unit "Biointeractions & Plant Health" at the Wageningen University & Research Centre in the Netherlands. He will deliver a presentation at CropWorld Global, which will be held at Amsterdam on October 29th-30th.*

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