CAN ORGANIC AGRICULTURE GIVE UP COPPER AS A CROP PROTECTION PRODUCT?

SUMMARY OF THE SCIENTIFIC ASSESSMENT REPORT - JUNE 2018

INRA
SCIENCE & IMPACT

Copper is used in many types of agriculture, and particularly in organic agriculture (OA), to control a variety of fungal and bacterial diseases, most importantly in vineyards, orchards, and vegetable production (including potatoes). It is the only active ingredient with a strong antimicrobial effect and a wide range of action that is approved for use in OA. In recent years, however, the demonstrated negative environmental effects of copper, notably on soil organisms and crop auxiliary species, have led to regulatory restrictions on its use (a maximum number of doses per hectare and per year) and even to its prohibition for use as a pesticide in several European countries (including the Netherlands and Denmark).

These increased restrictions on the number of authorized applications of copper, and the ongoing threat of a total ban, present a challenge for growers, and particularly for organic growers, who are prohibited from using synthetic fungicides. Significant demand thus exists for agricultural research to identify and develop "alternatives" to copper, and a variety of experimental trials have been conducted to test these alternatives. Results from this work are scattered, however, and there is no current comprehensive synthesis of research on the topic that would enable the development of guidelines based on validated and generalizable information. Practical adoption of alternatives to copper by farmers also remains limited.

*For these reasons, and at the suggestion of INRA's Internal Committee for Organic Agriculture (CIAB), the French Technical Institute for Organic Agriculture (ITAB) and the INRA Meta-program "Sustainable Management of Crop Health" (SMaCH) submitted a joint request to conduct a multi-disciplinary critical review and summary of all the available scientific and technical information on the subject of copper and alternatives to copper for pesticide use.The resulting Scientific Collective Assessment (*ESCo – Expertise Scientifique Collective*) explored: 1) the range of possible individual technical solutions (disease-resistant varieties; natural substances with biocidal effects and/or the capacity to stimulate natural plant defenses; antagonistic microbiological agents; management of crop canopies to prevent disease); 2) strategies to incorporate these solutions into existing production/pest management systems; and 3) barriers to and conditions necessary for the adoption and diffusion of these integrated strategies.*

This in-depth analysis of existing scientific and technical information found that numerous methods have some degree of efficacy against the pathogens targeted by copper-based products. However, it also found that a major reduction or total withdrawal of copper use will only be possible if these different methods can be combined within agricultural systems, in ways that remain insufficiently explored. These findings apply particularly to organic agriculture, which is more strongly impacted by restrictions on the use of copper and thus is more actively seeking alternatives, but they also address other forms of agriculture seeking to reduce pesticide use.

The use of copper for crop protection: target pathogens, environmental impacts, legislation

• The use of copper for crop protection

Indispensable for cellular life but toxic above a certain level, copper is widely used for its antimicrobial properties, both in agriculture and in human and veterinary medicine. The precise mechanisms by which it acts on microorganisms are unknown, although several hypotheses have been put forward (leakage of cellular electrolytes, disruption of osmotic balance, chelation at the active sites of certain proteins, stimulation of an oxidizing stress).

For crop protection purposes, copper is used primarily in its ionic form, in salt-based formulations (copper sulfate or copper hydroxide) accompanied by various adjuvants. Bordeaux mixture (copper sulfate + lime) is emblematic of this type of formulation. Such products are generally sprayed on to the above-ground parts of the crop. They can also be used as a seed treatment (for cereals) or applied locally (e.g., as a coating for pruning cuts, or to specific areas at the soil level).

• Target pathogens for copper

Copper-based products are used to control specific fungal and bacterial diseases. Fungal diseases targeted by copper are caused by ascomycetes (e.g., apple scab) or oomycetes (downy mildews), which have broadly similar life cycles: a survival phase, generally in or on crop residues close to fields (leaf litter, suckers/volunteers, piles of culled fruit, etc.), leading to primary infections, followed by epidemic extension (secondary infections), during which the pathogens spread more or less rapidly to a large number of susceptible plant parts (see Figure p. 4). Bacterial diseases targeted by copper are also characterized by polycyclic epidemics. Copper is used primarily to prevent secondary infections; it is very rarely used to reduce or destroy the primary inoculum, which is usually inaccessible to treatment applications.

The Scientific Collective Assessment (ESCo)

An ESCo is an institutional expertise activity, conducted according to the national charter for expertise provision adopted by INRA in 2011. An ESCo is defined as an activity for the assembly and analysis of information, produced across a wide range of fields of knowledge, relevant to the development and improvement of public policy. The information review and analysis is intended to be as complete as possible, but it is not intended to formulate specific recommendations, guidelines, or practical solutions to the questions confronting public decision-makers.

Any ESCo is undertaken by a multi-disciplinary group of expert researchers drawn from a variety of institutional backgrounds. The documentary corpus is assembled through a search of the international bibliographic database Web of Science (WoS). The exercise concludes with the production of 1) a full report compiling the contributions of the various experts, 2) a condensed report intended for use by decision-makers, and 3) a short summary highlighting the ESCo's key features and findings.

The "Alternatives to Copper" ESCo brought together ten national and international experts from a number of different institutions (INRA, universities, institutes, etc.). Their work was based on a bibliographic corpus of approximately 900 references, primarily scientific articles, to which were added a smaller number of technical documents.

Copper is approved for more than 50 different crop protection "uses", each use being defined as a combination of a crop and a target pathogen. Approved uses for copper primarily involve fungal and bacterial diseases affecting **perennial crops** (grapes, pome fruit, stone fruit, nuts), **vegetable crops** (a dozen genera belonging to several different botanical families), **perfume, aromatic, and medicinal plants** (PAMP); **ornamentals**; **seed-production** crops and diseases that develop on **tree wounds**. Among **major field crops**, approved uses for copper are limited to potato late blight and a handful of fungal diseases of wheat and rye that are transmitted by seed.

Three major uses for copper

Some uses of copper as a pesticide can be considered as "major" due to the land area covered and economic value of the crops involved, the yield losses caused by the disease, and/or the quantities of copper applied. Such uses are accordingly the focus of most research studies and experimental trials.

• ***Grape downy mildew****, caused by the oomycete* Plasmopara viticola*, is a highly damaging disease for grapes, particularly in oceanic climates. Its strong epidemic potential demands a highly effective level of protection, in the absence of which yields can be severely affected or even totally annihilated. Controlling downy mildew with a "contact" product like copper thus requires multiple applications (as many as 15 per year), especially given that the majority of grape varieties are highly susceptible to the disease. Vineyards accounted for 782,700 hectares of agricultural land in France in 2016.*

• ***Apple scab****, caused by the ascomycete fungus* Venturia inaequalis*, is a disease of considerable economic importance (scabbed fruit is not marketable). Effective control requires 10-20 applications of fungicide per year for susceptible varieties. Apple orchards occupied 36,500 hectares of land in France in 2016.*

• ***Potato late blight****, caused by the oomycete* Phytophthora infestans*, is the most serious disease affecting potato production. It regularly impacts yields and can result in the total loss of a crop. Potato late blight is present in all potato-growing areas, but more frequently causes severe damage in oceanic climates. Control is achieved with 10-12 fungicidal treatments per year on average, and up to 15-20 in high-risk areas. Approximately 200,000 ha of potatoes are planted in France each year.*

Apple scab

Downy mildew in grapes

Potato late blight

• Copper accumulation in soils, phytotoxicity for crops, ecotoxicity

Repeated application of copper-based pesticides is the most significant source of copper contamination of agricultural soils, and in some cases can lead to a massive accumulation of copper in the upper soil horizons. In Europe, the essentially uninterrupted application of Bordeaux mixture to combat downy mildew in grapes has led to substantial increases in copper levels in vineyard soils, with values reaching 200 or even 500 mg/kg (vs. 3 to 100 mg/kg in untreated soils).

Excess copper concentrations are recognized as having phytotoxic effects on the growth and development of most plant species, usually apparent in the form of chloroses and a reduction in total plant biomass. Some crops – including legumes, grapes, hops, and cereals – are particularly sensitive to high copper levels.

The deleterious effects of excessive copper on soil microbes are well established, as is copper's toxicity for some groups of soil fauna, such as the collembola (springtails). Impacts are more controversial for other groups, particularly earthworms (the lethal dose is relatively high for some species, but chronic toxicity is often observed, with measurable impacts on reproductive parameters and on worm physiology). It is thus reasonable to suppose that elevated copper levels in soils have long-term effects on earthworm population dynamics, as well as on other components of the soil fauna that are important to the functioning of biogeochemical cycles. Finally, copper applications can be toxic to fungal species that are used as biocontrol agents (e.g., *Beauveria bassiana*, which is used to control pest insects).

• Regulatory restrictions on the use of copper

Recognition of the negative environmental effects of copper-based products has led to the imposition of restrictions on their use. The use of copper for crop protection purposes is currently permitted in France and in the majority of other EU countries, in both conventional and organic agriculture, up to a maximum dose of 6 kg/ha/yr of elemental copper. Some countries have chosen to place stricter limits on the application of copper, however. Switzerland has set a maximum dose of 4 kg Cu/ha/yr for most crops (averaged over 5 years, with a maximum of 6 kg/ha in the case of intense disease pressure in a given year), 2 kg/ha/yr for small fruit, and 1.5 kg/ha/yr for nuts. Other countries (mainly the Netherlands and some Scandinavian states) as well as some growers' organisations and certification bodies (Demeter in Germany, for example) have chosen to totally ban crop protection uses of copper in both conventional and organic agriculture, although the use of copper as a fertilizer remains allowed. Most certification bodies for biodynamic agriculture prohibit the habitual use of copper as a crop protection agent.

• Actual quantities of copper applied

Three recent surveys conducted **among organic farmers** in France and Switzerland found that although the quantities of copper applied by farmers are often significantly lower than the maximum allowed amount, the use of copper nevertheless remains high. **In Switzerland**, copper applications are nearly 3 kg/ha/yr in potatoes and vineyards (for susceptible varieties), 2.5 kg/ha/yr in cherry orchards, and 1 kg/ha/yr in apple and pear orchards; these application rates amount to 60-80% of the maximum allowance. **In France**, the use of copper in organic grape production averages nearly 5 kg/ha/yr in years of intense downy mildew pressure (roughly one year out of two), with significant regional disparities: 1.6 kg Cu/ha/yr in Alsace, 5.6 kg in the Loire Valley, and up to more than 6 kg in Champagne, Midi-Pyrénées, and Languedoc-Roussillon. Year-to-year variations are also pronounced: average use in France is 3 kg Cu/ha/yr in low disease-pressure years, vs. 5 kg in high disease-pressure years. The same survey found similar trends in fruit production and vegetable crops.

Alternatives to copper: a wide range of partially effective methods

An abundance of scientific and technical publications testifies to the active level of academic and applied research efforts to identify and evaluate alternatives to the widespread use of copper. Results obtained in this field could also potentially be transposed or extended to other pesticides targeting the same pathogens. While a considerable volume of information is thus available, it is very unevenly divided between the areas of research and development. In addition, most efforts to date have focused on the description of individual practices and strategies, as opposed to the integration or combination of such practices within an overall production system.

• Modes of action of alternative methods

Available alternatives to copper can be divided into three major groups according to their underlying mode of action with respect to the life cycle of the targeted pathogenic agent (see figure below).

• **Products or methods that act directly on the pathogen itself**, including the application of biocidal substances (e.g., plant extracts with anti-microbial properties) or the use of other organisms with a direct, antagonistic effect. Such products can impede spore germination or other phases of pathogen development, for example pathogen growth *in planta* or pathogen reproduction.

• **Products or methods that make use of the natural capacities of plants for resistance**, whether constitutive (*i.e.* the creation of **resistant varieties** by exploiting the genetic resources of the cultivated species or closely related species) or induced by infection or external stimuli. So-called **plant defense stimulators** (PDS) take advantage of natural plant defense mechanisms to block tissue colonization following infection.

• **The use of agronomic practices to prevent primary infection (prophylaxis) or secondary infection (avoidance).** The first category includes careful management of potentially infected crop residues. The second typically involves covering or protecting crops with rain shelters so as to minimize spore germination and infection: preventing the contamination of leaves by airborne or splash-borne spores, reducing exposure of the growing crop to humid or wet conditions, limiting wind and/or hail damage, etc.

The term **"biocontrol"** is used to designate both direct-action methods based on natural substances or products (thus not including synthetic mineral or organic preparations, such as copper salts), biological control, and the stimulation of plant defenses using naturally derived (non-synthetic) products. It is important to note that not all biocontrol methods are *ipso facto* eligible for use in OA, and that some methods used in OA (such as the use of copper at various doses) do not fall into the category of biocontrol.

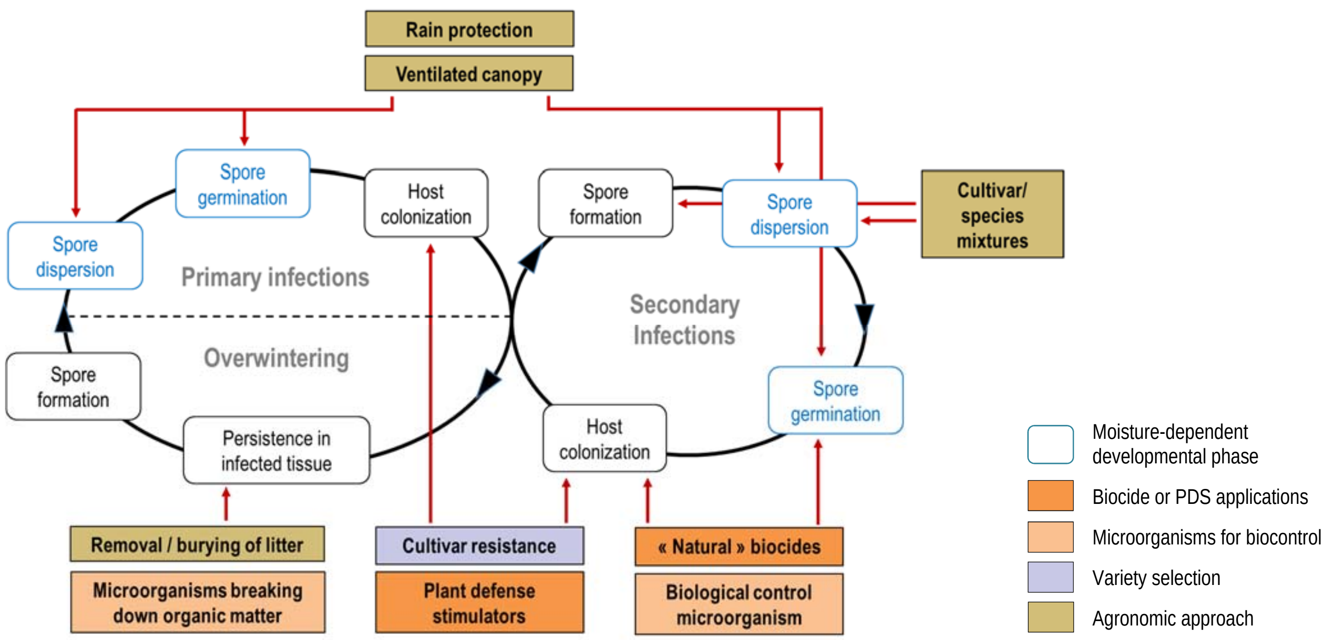
• Assessing efficacy

The efficacy of a crop protection method can be measured in terms of its impact on the frequency (incidence) or severity of symptoms, yield losses caused by the pathogen, or the quantity of pathogen spores present in the environment. Evaluations are made of comparative efficacy between or among different crop protection methods, in OA and/or in CA. The efficacy of an alternative method can thus be compared to the efficacy of standard treatments using copper or to the use of a reference synthetic pesticide. Many trials also assess the efficacy of the alternative method when used in combination with a reduced level of copper.

An alternative method can be considered promising even if it does not provide sufficient protection on its own for commercial production. Distinctions made between different production contexts (growing seasons, the susceptibility of a specific crop variety) exhibiting low or high disease pressure can help identify alternative methods that are sufficiently effective under certain conditions.

A close analysis of scientific findings, including an assessment of knowledge gaps in certain areas, suggests several important conclusions with respect to the effort to reduce and/or eliminate the use of copper as a crop protection product.

Disease-management alternatives to copper,
showing mode of action on the pathogen life cycle



▶ Individual solutions with partial efficacy…

• Direct action on the pathogen

o The use of **natural preparations or extracts with biocidal properties** is an active focus of current research. Often of complex composition, these preparations frequently have a stimulating effect on plant defenses, in addition to their biocidal properties (this is true of phosphites and of many essential oils, for instance). The strong antimicrobial properties of these materials under controlled conditions has suggested some promising potential substitutes for copper, although product formulation remains a challenge. Using these products may also be problematic due to undesirable effects on the harvested crop (organoleptic qualities, residue buildup) and/or questions as to the status of some formulations with respect to organic agriculture certification (phosphites are prohibited under current rules, for example).

o Another area of research is the use of **biological control organisms**, which can act against pests by way of antagonism, hyperparasitism, or ecological competition. Systematic efforts are underway to identify species and strains with strong pest-management potential. Nevertheless, few of the products currently available are approved for use against the disease agents targeted by copper, and even those strains and species in the early stages of research are far from covering the range of applications supplied by copper-based materials. There is thus little current promise of microbiological control materials to take the place of copper. Future development of such products faces marketing and regulatory challenges (effective formulation, regulatory approval) as well as the question of efficacy in the field.

• Exploiting plants' capacity for resistance

o **Resistant varieties**, developed within the context of specialized breeding programs, are available and effective against many of the diseases targeted by the use of copper, including those representing a major percentage of copper applications (potato late blight, downy mildew in grapes, apple scab, etc.). These varieties can either provide **total resistance**, usually controlled by a simple gene and resulting in a total absence of symptoms or in small, localized necroses at the point of infection (super-sensitive reactions); or **partial resistance**, usually controlled by a more complex genetic determinism (multiple loci or QTL) and resulting in a slowing down rather than a total absence of disease development.

Despite the availability of resistant crop material, the use of such varieties remains relatively limited. This apparently paradoxical situation is explained by farmers' and other users' concerns with respect to: 1) the durability or longevity of the resistance phenotype, even when this can be strengthened by complex genetic constructions at the plant level ("pyramiding" of genes or QTL within a given genotype) or at the level of the crop population (associations of varieties or species within a given field); 2) the unfavorable effect of resistance on other agronomic characteristics (yield, earliness) or on crop quality criteria (flavor, food value); 3) the origin of the resistance trait within the released variety, particularly those introduced using genetic engineering or biotechnology (interspecific crossings, GMOs, new breeding techniques like genome editing), which many producers are skeptical of or opposed to; and finally 4) the difficulty of changing varieties when other solutions (e.g. pesticides, including copper) are available to manage crop health. The last issue is especially challenging for farmers producing under quality labels such as the appellation system for wines, in which grape varieties are strictly controlled and the majority of the allowed varieties are disease-susceptible. This type of "lock-in" is found in production systems both in developed countries and in developing and emerging countries.

o **Plant defense stimulators** (PDS) are another active area of research. Numerous products and molecules with proven biological activity under laboratory conditions have been identified. Many of these (phosphites, extracts obtained from micro-organisms, etc.) appear to have multiple modes of action, with both direct biocidal effects and plant defense-inducing effects. Transferring these properties from controlled conditions in the laboratory to field conditions has proven challenging, with protection weakening or becoming inconsistent. This could result from difficulties in product formulation (the material must be able to penetrate the plant in order to be recognized), treatment timing (defense stimulators must be applied prior to infection, whereas many biocides are most effective when applied in the presence of the target organism), persistence of the effect over time, or even from biases in the evaluation methods. These questions have scarcely been studied or analysed, with most work currently being dedicated to the search for molecules and products showing demonstrable effects in the laboratory. It should be noted that synthetic PDS available for use in conventional agriculture are more effective (and in some cases less phytotoxic) than the natural PDS allowed in OA.

o Methods based on **homeopathy** and **isotherapy** (**also called isopathy**) are poorly documented, but seem to be of debatable efficacy and do not appear to provide a credible alternative to other possibilities. They are rarely examined in academic and technical publications, and very few scientific data are available on the topic.

• Agronomic practices to combat primary infection

o A variety of **physical practices** can be used **to limit the survival of residual inoculum in the field** (removal of infected crop residues, management of volunteers/suckers, etc.) or **inhibit the inocula's access to harvestable plant parts** (burying, tarping, selection of disease-free seeds and plants). Such methods have been shown to be highly effective in controlling disease, but often present a challenge for the producer. For example, protecting fruit trees from the rain can be expensive, even where it can be combined with anti-hail protection or insect netting, which are already in widespread use.

o Other **crop management practices** show promise for limiting the number of epidemic outbreaks, in particular those practices making use of **spatial and temporal diversification of crop varieties** at the field level (associations of varieties or species to inhibit secondary infection) or at the landscape level (landscape mosaics, crop rotations). These strategies can significantly limit the spread of secondary infections but likewise impose relatively heavy agronomic constraints, both in terms of farm management and in terms of the marketing and sale of the crop.

… that remain insufficiently integrated into overall crop protection systems

Although the testing of new materials and product formulations is on the rise, it should be noted that very few tools have been developed to assist farmers in the selection and use of these products; indeed, few such tools appear to be even in the process of development. This is true for Decision Support Systems (DSS) specific to biocontrol, for example, as well as for assessments of crop genotype responses to new product formulations (e.g., PDS).

For the most part, moreover, alternative products and methods have been considered and tested as one-for-one substitutes for chemical applications, whereas given their limited efficacy and the risks associated with their durability (for instance the risk of a loss of varietal resistance.), they should in practice be integrated within broader, more complex strategies for crop protection. Unfortunately, evaluation studies of alternative methods are more often designed from a simple substitution perspective (replacing copper with an alternative product or an alternative practice) than from the perspective of a redesign of crop protection and crop production systems. Studies focused on the design, testing, and multi-criteria assessment of integrated pest management systems including the alternatives reviewed here, with the objective of a total or partial elimination of the use of copper, are (too) few and far between. Only a handful of references and limited scientific data are available on the characteristics and performance of integrated systems (including at the landscape level, such as agroforestry). In the absence of appropriately calibrated and sufficiently precise models, the design and evaluation of such systems remains a challenge.

▶ Giving up copper: significant room for improvement

• A significant reduction in copper use is possible without otherwise changing existing cropping systems

A large number of studies covering a range of diseases (including potato late blight, downy mildew on grapes, apple scab, and others) show that **reducing the amount of copper applied by one half**, usually by maintaining the same application schedule but reducing the application rate for each pass while improving spray quality, **results in most cases in an identical or comparable level of control** to that obtained with sprays at standard rates. In other words, a satisfactory level of protection with respect to these diseases can be achieved with the use of 1.5 kg of copper element per hectare per year, vs. the 3 kg/ha/yr currently used in most "standard" spray programs. This is true when disease pressure is not excessive; when disease pressure is high, the maximum legal rate (6 kg/ha/yr) is still sometimes required to achieve satisfactory control. It follows that a significant reduction in the allowed amount of applied copper would not create an unworkable situation or pose a total threat to crop output, except in cases of severe disease pressure.

• Experimental systems without copper are effective…

Several pilot experiments, particularly those conducted within a group of European projects known as *Blight Mop*, *RepCo* and *Co-Free*, have demonstrated that complex systems associating multiple alternative mechanisms (variety resistance, PDS, agronomic practices such as crop associations, sanitation, etc.) can offer equivalent disease-control effectiveness to systems relying on a typical disease control program using copper. Most of these results have been obtained under experimental station conditions, but some have been obtained in on-farm trials. Success with these types of alternative management systems appears easier to achieve and to replicate with annual than with perennial crops (such as fruit trees, viticulture); not surprisingly, situations with fewer obstacles to the use of resistant varieties (e.g., non-AOP production) are also more favorable. It should be noted however that levels of disease-control efficacy are highly variable depending on environmental conditions and on the combination of methods used. These conclusions should be considered as preliminary given the limited number of cases involved.

… their effectiveness is strongly dependent on certain system elements…

These trials suggest that **resistant varieties are essential to crop protection systems eliminating copper.** Resistant varieties can be deployed in combination with strategies to help strengthen and preserve their efficacy over time and space (e.g., the use of varietal associations). Variety resistance can also be reinforced by preventive measures seeking to eliminate inocula in the field (e.g., collecting or shredding infected plant material) or by impeding inocula's access to the developing crop (covering). On the other hand, the management of fertilization regimes (type and quantity), and the use of biodynamic or isopathic preparations have generally shown little effectiveness.

… and their further diffusion will require changes at every level of the production chain

The adoption of such systems, which potentially imply major alterations relative to the current standard, also requires a significant readjustment of production chains: the development of markets for alternative crops associated with longer crop rotations; supply networks that can handle a wider range of products; label claims to add value to products grown without copper; etc. Initiatives such as the development of growers "clubs" to promote the use of resistant varieties or the revision of AOP rules with respect to variety requirements also deserve further attention.

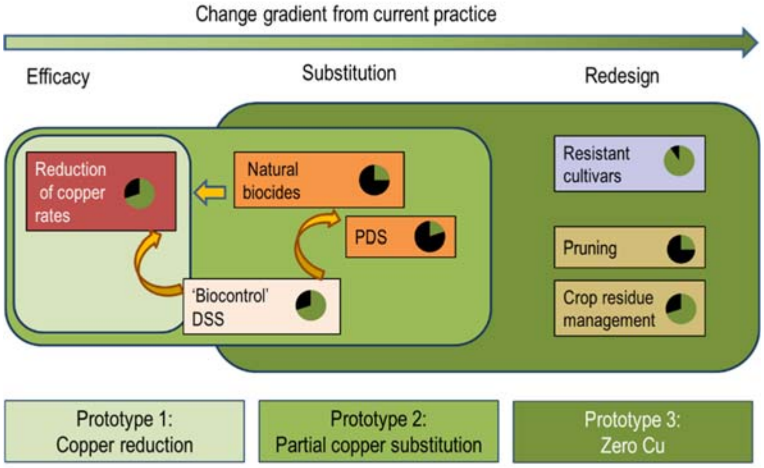
▶ Prototypes to be imagined… and tested?

The information assembled for this ESCo suggests the possibility of developing a set of prototype crop protection systems – at this stage purely hypothetical – designed to achieve a range of specific objectives: e.g., replacing all copper products without altering other system elements; identifying a maximum level of protection that is sustainable over time, etc. This exercise was accordingly performed for the three diseases for which the most information was available, using the conceptual framework known as "ESR", for *Effectiveness* of inputs (input optimization within a logic of "smart" or precision agriculture), *Substitution* of contentious inputs or strategies, and *Redesign* of the cropping system within a logic of integrated management.

The approach adopted for the development of the prototypes was as follows: i) assume the availability of a series of alternative crop protection methods and/or products (either currently available or likely to become available in the future based on published research results), positioned along a gradient of change relative to current practices; ii) indicate for each their anticipated effectiveness relative to no intervention (non-treated control); iii) specify the system objectives for each disease complex: three scenarios of increasing ambition with respect to the elimination of copper; and iv) identify compatible combinations of methods to achieve these objectives. Due to insufficient data, neither the costs necessary to implement these prototypes nor their consequences for the management of other potential pest problems were considered.

Theoretical prototypes for crop protection systems to reduce the use of copper

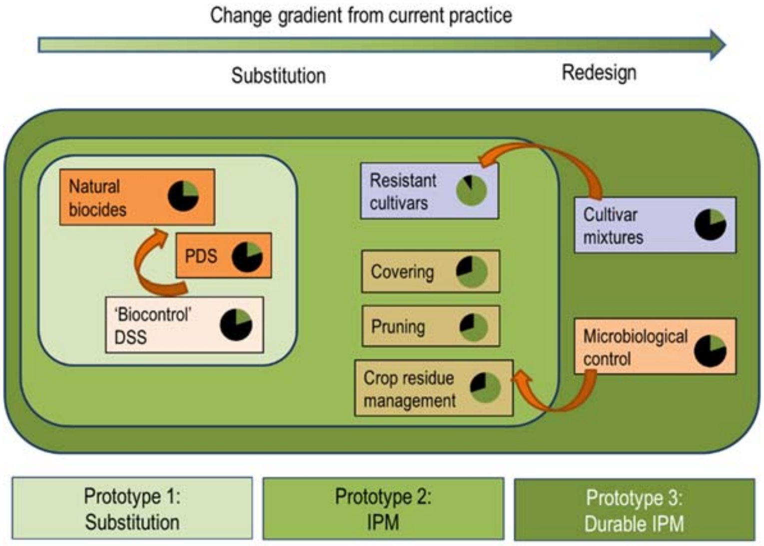
Case 1: Downy mildew in grapes



This is without question the most challenging of the three cases presented here. A limited number of alternative strategies are available, and some of these (e.g., resistant varieties) are difficult to introduce into existing production systems.

Prototype 1 targets protection using low or very low levels of copper. It is based primarily on a direct reduction in copper application rates, making use of a decision-making tool (such as Mildium*) to determine the optimum dosage and timing of applications. Prototype 2, "partial substitution," combines a reduced use of copper with the use of PDS or biocidal preparations in place of some copper applications. Prototype 3, finally, seeks to provide protection with "zero copper." In addition to the biocontrol products used in Prototype 2, it requires the obligate adoption of resistant varieties, as well as disease prevention measures such as the removal of infected leaf litter and the management of the microclimate* via *specific pruning strategies.*

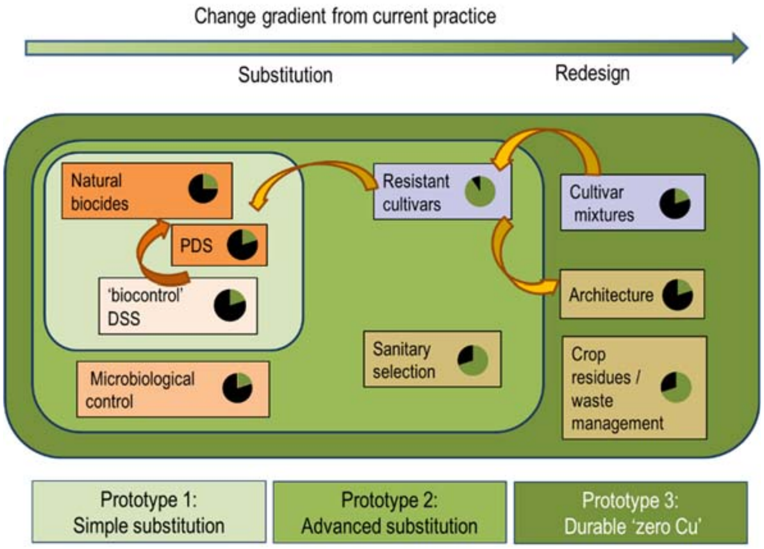
Case 2: Apple scab



This case has the largest number of available alternative strategies, making it possible to construct all three prototypes assuming no use of copper.

In Prototype 1, the objective is simply to replace copper treatments with biocontrol products (PDS or biocides), selected and timed using a tailored decision-making tool. Since these products have only limited individual effectiveness, it is likely that such a system would only be satisfactory in terms of crop protection efficacy in situations of very low disease pressure. Prototype 2, targeting integrated protection without copper, would add to these biocontrol solutions 1) the use of resistant varieties and 2) the use of preventive methods to sharply limit the pressure of inocula in the field (rain shelters, 'open vase' pruning, removal or burying of infected litter). Finally, Prototype 3 (integrated sustainable pest management) seeks to strengthen the potential weak points of Prototype 2: planting mixed varieties within orchard rows to reduce the risk of loss of varietal resistance; and using microbial antagonism or hyperparasitism to reduce the production of primary ionoculum on litter and limit inoculum sources external to the plot.

Case 3: Potato late blight



As in the previous case, all three prototypes were constructed on the basis of a total elimination of copper.

In Prototype 1, the objective is simply to replace copper treatments with biocontrol products (PDS or biocides), selected and timed with the help of a specific decision-making tool. As in the case of apple scab, the limited individual efficacy of these products will most likely make this prototype insufficiently effective, particularly in climates highly favorable to the parasite. Prototype 2 targets a higher level of substitution, notably by making use of the most resistant varieties available and strict adherence to sanitation practices, particularly for farm-grown (uncertified) seed potatoes. These methods should improve overall efficacy, but remain vulnerable to the fragility of most highly effective varietal resistances. Prototype 3, "long-term zero copper" reinforces this resistance with other strategies (plant architecture to minimize the spread of disease, mixed-variety plantings, additional reduction of parasite pressure through careful management of crop residues and other plant materials in proximity to production fields).

Legend: the green sectors of the small dials indicate the effectiveness of each strategy; the color key for the small rectangles is the same as in the figure on page 4.

▶ Several research avenues critical to the elimination of copper have been insufficiently explored

Achieving an effective level of crop protection without the use of copper often requires a total redesign of crop protection systems, and even of crop production systems. The analysis provided by this ESCo suggests that there are three major areas of research essential to this process of systems re-conception that have been significantly underinvested in by the scientific community.

The first relates to the field of plant pathology. Research needs here include: i) the development of management tools specific to alternative methods (e.g., decision-making tools designed to support the use of plant defense stimulators and microbiological control agents); ii) strategies to address combinations of pest pressures within a single crop, rather than single pests alone (in other words, a greater emphasis on integrated pest management); and finally, iii) assessments of the sustainability and durability of alternative pest management strategies, methods, and products.

A second area of research in need of further investment relates to systems agronomy. This includes two specific lines of inquiry that have received little attention to date: i) tools and methods for the development of innovative crop protection systems involving little or no use of synthetic pesticides (e.g., rules for the effective combination of different pest management methods or materials, tools to assist in the planning and timing of tactical interventions); and ii) methods to evaluate such integrated systems over the long term. A few pioneering publications have begun to examine these questions, but they have been limited to relatively specific contexts (mainly perennial crops and large-scale industrial field crops) and have given little attention to vegetable crops or other specialty crops. Further work in this field is needed.

Finally, a third area that has been insufficiently explored relates to the economic sciences. Research needs here include detailed analyses of the economic consequences for farmers of the adoption of alternative crop protection methods (relative price of materials, labor expenses, etc.). Equally important are studies of the industrial strategies and decision-making taking place upstream of the farm level, the impact of these strategies on the availability and diffusion of key innovations, their variability as a function of market structures (mainstream vs. niche markets), and the relative importance of different industrial actors (e.g., major agrichemical companies vs. smaller companies or start-ups). One could hypothesize for instance that the limited financial resources of start-up companies (the only players concentrating exclusively on the market for biocontrol products, generally by making use of public – and thus non-patentable – research materials) give them limited R&D and marketing capacity, leading them to pursue minimal levels of regulatory approval (e.g., approval as a "fertilizer" rather than as a crop protection product) and restricting their ability to distribute products that have been approved. At the other end of the spectrum, the major agrochemical companies have begun to enter the biocontrol market *via* the purchase of start-ups and specialized SMEs, and are presumably able to pursue broader research and marketing strategies, drawing on much greater financial resources, to ensure the development and promotion of alternative crop protection solutions. Economists and sociologists of innovation might find the emerging field of biocontrol to be an interesting case study for the examination of these hypotheses.

▶ Lessons for and from "conventional" systems

Opportunities and barriers to the development of disease-management methods and systems for organic agriculture that exclude the use of copper are identical to those encountered in the search for alternatives to pesticide use in 'conventional' (i.e., non-organic) agriculture. Many of the potential solutions are the same (resistant varieties, biocontrol, increased use of preventive sanitary measures, etc.). Many of the questions that arise are also comparable: the degree of change necessary to ensure adequate crop protection, the possibilities and challenges of organizing combinations of partially or temporarily effective measures within an integrated sequence of protection strategies. The impacts on work organization and production chains, the acceptability of innovations, and the ability to overcome socio-technical conundra are also similar. For all these reasons, organic agriculture and other forms of agriculture could mutually benefit from more coordinated approaches to research on these questions, provided that the results are interpreted to address the specific needs of each production system.

To learn more

Andrivon D., Bardin M., Bertrand C., Brun L., Daire X., Fabre F., Gary C., Montarry J., Nicot P., Reignault P., Tamm L., Savini I., 2018. *Can organic agriculture give up copper as a crop protection product?* Condensed report of the Scientific collective assessment, INRA, 66 p.

This document as well as the full assessment report (in french) are available on the INRA website (www.inra.fr).

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