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Can organic agriculture cope without copper for disease control?

Synthesis of the Collective Scientific Assessment Report

Didier Andrivon, Isabelle Savini, eds

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This book summarizes the collective scientific assessment report jointly requested in 2017 by the French Technical Institute for Organic Agriculture (ITAB) and the Sustainable Management of Crop Health (SMaCH) metaprogramme of INRAE. The contents of the full report and this abridged version are the sole responsibility of the authors. The overall report, source of this version, was created by the scientific experts without condition of preliminary approval by the sponsors or INRAE. The abridged version was validated by the authors of the report.

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Introduction

Significant uses of copper, subject to increasing levels of regulation

Since the advent of Bordeaux mixture in the late 19th century, copper has been a major element in crop protection methods against a variety of fungal and bacterial diseases of plants, particularly in viticulture, fruit, and vegetable production. Copper is used in a range of "conventional" agricultural systems, in combination with other pesticides, but it plays a critical role in most organic agricultural systems (OA). It is currently the only active ingredient approved for use in OA that has both a strong biocidal effect and a wide spectrum of action.

While most uses of copper are justified by their biological effectiveness, they also generate ecotoxicological problems (proven risks for soil microbial populations, earthworms, some aquatic organisms, and beneficial microbes). The demonstrated environmental impacts of copper have led to regulatory restrictions on its use (e.g. a maximum allowable application rate per hectare per year), and even to its total prohibition as a pesticide in some European countries (such as the Netherlands or Denmark). This situation creates an uneven competitive landscape for organic growers across Europe.

Alternatives to the use of copper: considerable research prompting the need for a critical synthesis

The increased restrictions on the amount of copper growers can apply, together with the looming threat of a total ban at the European level, presents a challenge for organic growers who cannot replace it by other synthetic pesticides. A recurrent demand thus exists for research on "alternatives" to copper. First articulated some twenty years ago, the need for viable alternatives to the use of copper continues to appear on recent lists of agricultural research priorities (for example, within the French framework programme for OA development *Ambition Bio*).

As a result, the question of "alternatives" to copper has been the focus of considerable research and R&D activity, including three major European research programs since the beginning of the 2000s alongside numerous other prominent, but more limited, research efforts in different parts of the world. Countless trials of alternative methods and products have been conducted, both by technical centers and by growers themselves, to evaluate the potential of different molecules and/or formulations. Other research has focused on elucidating the underlying biological mechanisms involved (in particular the elicitation of plant defenses, the ecology of disease organisms and of biocontrol agents, etc.).

While a significant number of scientific and technical references has thus been accumulated, practical adoption of these potential innovations remains limited. Relevant findings are scattered across a variety of sources, are often fragmentary in nature, and are not always readily accessible. No complete critical synthesis of this research has been published to date. Scientists and technicians alike lack access to a consolidated "state of the art" on the topic, one which offers a scientific evaluation of the efficacy and limitations of the various possible alternatives to copper. Such a review could assist in identifying research priorities and developing recommendations for the practical implementation of these alternatives.

Organization and intent of a Collective Scientific Expertise

Within this context, and in response to a series of meetings with relevant stakeholders, INRA's Internal Committee on Organic Agriculture (CIAB) suggested that a critical analysis of the full range of available and validated information on the subject should be undertaken. This suggestion was taken up by the French Technical Institute for Organic Agriculture (*Institut Technique de l'Agriculture Biologique* - ITAB) and by INRA's metaprogramme "Sustainable Management of Crop Health" (SMaCH), which jointly requested a Collective Scientific Assessment (*Expertise Scientifique Collective* – ESCo) – a multidisciplinary, critical review of all the relevant scientific and technical information – on the topic. This type of exercise is conducted at INRA by its Delegation for Collective Scientific Assessment, Foresight and Advanced Studies (*Délégation à l'Expertise scientifique collective, à la Prospective et aux Etudes* – DEPE), following clearly established rules and procedures (Box I.1). An ESCo consists in the critical analysis of the existing international scientific literature on a topic (with an emphasis on academic research) by group of scientific experts (researchers from public research and higher education institutions). While an ESCo is intended to provide clarification, it does not formulate specific recommendations.

The goal of the ESCo was to produce a summary of *published* information that could be used by stakeholders to guide their decisions with respect to research or R&D efforts seeking to favor the emergence of "zero copper" or "very low copper" disease management strategies, and applicable in organic agricultural systems. Its scope was to include:
• the range of possible technical solutions: treatments based on natural substances with biocidal effects and/or which act to stimulate natural plant defenses; the introduction of microbiological control agents; the use of disease-resistant crop varieties; and the management of crops and crop areas to prevent the spread of disease;
• the insertion of these individual solutions within integrated production/crop protection systems;
• constraints and necessary conditions to the diffusion and adoption of alternative methods.

The ESCo considered *a priori* all approved "uses" (combinations of *crop x pathogen*) for copper-based treatments, placing an emphasis on a small number of "major" uses (in terms of the economic importance of the crops involved). These uses for copper have received the most attention from researchers and are the focus of the largest number of published references.

The analysis focused on the case of OA, which is both the mode of production most dependent on copper and the context addressed by a large number of the available references. Nevertheless, the ESCo findings are relevant to all forms of agriculture seeking to reduce the use of synthetic pesticides.

Status and organization of this document

The present document is a synopsis of the full report (in French) produced by the expert group, available on the INRA website. Only a few key bibliographic references are cited here; a complete bibliography is included in the experts' report.

The first chapter provides background information, which is not in itself the focus of the Collective Scientific Expertise. These background data relate to copper (approved uses, regulatory restrictions and the reasons for these restrictions, actual use in agricultural production contexts, etc.) and alternatives to copper (the range of possible techniques, general rules for regulatory approval and authorization, etc.). It specifies the documentary sources available with regard to these alternatives.

The second chapter describes the various technical means available or proposed to control pathogens, either directly (by killing the pathogen or limiting its development) or indirectly (by increasing crop resistance): natural biocidal preparations, microbial biocontrol agents, plant genetic resistance, stimulators of natural plant defenses, homeopathy and isopathy, etc.

The third chapter focuses on agronomic strategies designed to limit plant health risks: prevention measures to reduce sources of contamination (removal of infected plants or crop residues, etc.); physical protection against infection (rain and/or hail protection); and crop or planting management methods (pruning and training of fruit trees, planting of mixed covers, etc.) intended to create conditions unfavorable to the development and spread of disease.

The fourth chapter considers information available at the level of the cropping systems, as well as the impediments that exist with respect to the development and adoption of innovations within these systems.

A concluding chapter summarizes the lessons that may be drawn from this analysis, including the current availability of alternatives to the use of copper, the possibilities for further implementation, and continuing research needs. In addition, it proposes a set of theoretical prototypes for integrated protection systems for the three most important agricultural uses of copper.

Box I.1. The Collective Scientific Assessment (ESCo)

The ESCo is an institutional expertise activity, governed by a national charter for expertise signed by INRA in 2011. It is defined as an activity for the assembly and analysis of scientific knowledge in diverse fields relevant to the clarification of public decision-making. The review and analysis is as complete as possible, but is not intended to provide specific advice, recommendations, or direct answers to the questions faced by public policymakers: its sole objective is to provide a critical review of scientific information, including points of debate and knowledge gaps, to support decision-makers in considering the actions available to them. The analysis is conducted by an interdisciplinary group of expert researchers from a range of institutions. For the ESCo on “Alternatives to Copper,” a dozen experts from different research institutions were involved. Their work was based on a literature corpus of nearly 1000 references, primarily scientific articles, and supplemented by technical documents. The exercise concludes with the production of a report (in French) consisting of the individual experts’ contributions; a synopsis (in French and in English) intended for use by decision-makers; and a short summary (in French and in English) intended for a more general audience.

1. Background

Copper: properties and uses

Biological properties and toxicological and ecotoxicological profile of copper

Copper is important for all living systems. It is a vital element involved in electron transport and thus in energetic metabolism; it also has antimicrobial properties. The precise mechanisms underlying the biocidal effects of copper on microorganisms have not been fully elucidated yet, although a number of hypotheses have been proposed: loss of electrolytes across the cellular membrane, creation of an oxidative stress, disruption of the ionic balance, blocking of normal protein functioning *via* chelation on active protein sites… A consensus is emerging among researchers that numerous organisms use the regulation of copper homeostasis – from a vital component to a cellular poison – to fight microbial infections. The antimicrobial properties of copper are the basis of a variety of applications for the management of human, animal, and plant health.

Formulations using copper

For its plant health applications, copper is used primarily in its ionic forms, in formulations based on copper salts (copper sulfate or copper hydroxide) combined with various adjuvants. The classical 'Bordeaux mixture' (copper sulfate + lime) is typical of this type of formulation. These products are generally used as sprays on above-ground plant parts; they can also be used for seed treatments (primarily for cereals) or as local applications (wound dressings for tree cuts, drenches to the seeding bed, etc.).

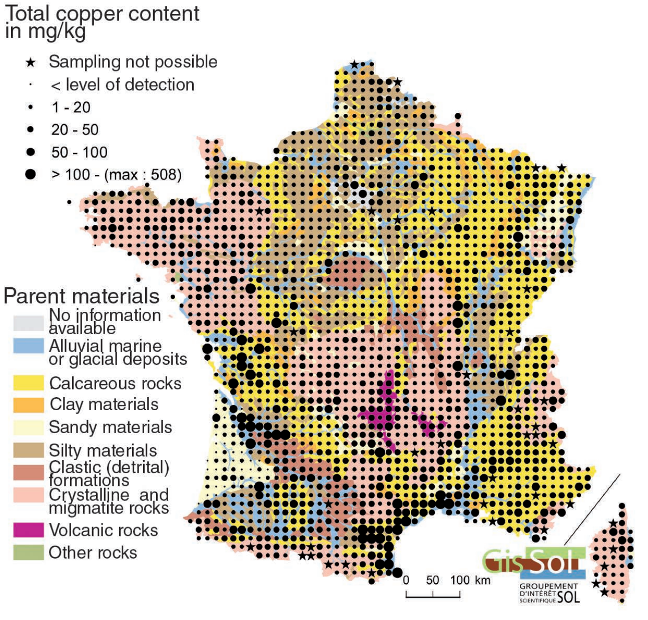
More recently, methods have been developed for the use of copper oxide nanoparticles (nano-CuO and nano-$CuCO_3$) that can be applied or incorporated into various materials (e.g. textiles)These nano-copper materials can act for instance as biocides for the treatment of wood and wood products against fungi and insects responsible for biodegradation.

Copper accumulation in soils

Copper concentrations in natural soils range from 3 to 100 mg/kg, depending on the underlying substrate and the soil type, and from 5 to 30-45 mg/kg in non-contaminated agricultural soils. In the latter, copper levels in the soil solution are generally very low (on the order of 1 to 10 µM, depending on the soil type), with an important fraction of the copper present being retained on clay-humic matrices.

Human activities, and particularly the repeated application of copper-based pesticides, are the main source for copper pollution in agricultural soils. They cause an accumulation, sometimes massive, of this metallic element in topsoil horizons (Figure 1.1). In Europe, the almost uninterrupted use of Bordeaux mixture to control grape downy mildew thus raised very strongly copper concentrations in wineyards, up to 200, and even sometimes 500 mg/kg.

Figure 1.1. Total copper contents in topsoil samples (0-30 cm) of the Soil Quality Monitoring Network.



Source: Gis Sol, RMQS, 2011; INRA, BDGSF, 1998

Phytotoxicity for crops

Excess copper concentrations have known harmful effects on the growth and development of the above-ground and below-ground parts of most plants, resulting in a decrease in total biomass. Some plant families and species, including legumes, grapevines, hops, and cereals, are particularly affected.

Copper toxicity is directly linked to the bioavailability of copper ions. Copper concentrations over 2 µM in nutrient solutions can be toxic for plants. A large part of their toxic effect comes from the inhibition of photosynthesis and the degradation of chloroplasts, resulting in more or less severe chlorosis. By disrupting the plant's oxidative metabolism, excess copper also triggers the plant general defenses, which comes at a metabolic cost.

Copper applications can also have an effect on the physiological composition and thus on the quality of harvested products. For example, they can reduce polyphenol levels and thus the anti-oxidant properties of olive leaves, and they can modify the concentration and balance of aromatic compounds in hop flowers.

Scientific research conducted in the 1990s on different plant species growing on heavily contaminated mining sites found that such accessions could be used to increase the plants' tolerance of excess heavy metals, with potential applications for the bio-remediation of contaminated soils. To our knowledge, however, the capacity to tolerate high soil copper levels has not been a focus of breeding programs in any plant species of agricultural interest.

Ecotoxicity

The deleterious effects of excess copper on soil microbial communities are well established. It is, after all, because of its antimicrobial effects that copper is used in agriculture. Given that fungi and bacteria play a critical role in trophic webs and in the completion of biogeochemical cycles, it is hardly surprising that disruption of soil microbial communities can lead to an impoverishment of locally available resources for other ecosystem consumers.

The toxicity of copper for specific components of the soil fauna, such as the springtail *Folsomia candida*, has also been shown. Impacts on other indicator species, such as earthworms, are less clear. Estimates of lethal copper concentrations for adult worms vary: some studies have found significantly increased mortality rates at concentrations of 150 mg/kg of soil, whereas others have found no effect at these levels. Copper seems to have a low acute toxicity for the earthworm test-species *Eisenia foetida*, with median lethal concentrations (LC_{50}) above 5,500 mg/kg of dry soil in laboratory conditions. At lower levels, chronic toxicity for earthworms is often observed: delayed sexual maturity, reduction in the number of cocoons, reduced hatching rates. Quantities of copper that show no measurable impact on these lifecycle parameters can still have observable effects on worm physiology. It is thus reasonable to assume that copper contamination of soils has long-term chronic effects on earthworm population dynamics and other soil fauna components that are important to the maintenance of soil structure and biogeochemical cycling. Copper applications are also toxic for fungal species used as biocontrol agents (for example, *Beauveria bassiana*, used against pest insects).

Nanoparticles containing copper can also be toxic for the plant-soil system, although it is not clear whether this toxicity is caused by the nanoparticles themselves or by an associated release of copper ions. Effects on plants are similar to those caused by an excess accumulation of copper ions in soil: a dramatic reduction in growth of the exposed plants and a modification of the ionic balance in plant tissues. Effects on soil microbial communities (attributed generally to the release of copper ions) have not been described in detail, but have been shown: reductions in microbial diversity, reductions in soil bacterial communities favorable to plant growth, reductions in iron uptake by both plants and microbes. It would appear that these nanoparticles also have a serious impact on other environmental compartments, particularly wetlands: fish, crustaceans, and algae all appear to be more sensitive than soil bacteria to the toxicity of copper oxide nanoparticles.

Uses of copper for crop protection

Approved uses

Copper is approved for crop protection uses against a variety of diseases due to fungi, bacteria and oomycetes, mainly on grape, fruit crops, and vegetable crops (Table 1.1 and Box 1.1).

Table 1.1. Currently approved uses of copper in France

	Crops	Diseases/pathogens	
		Bacterial diseases	**Fungal diseases**
Fruit trees & grapes	Citrus	*Xanthomonas axonopodis* pv. *citri*, *X. axonopodis* pv. *citrumelo*, *X. citri* subsp. *citri*	
	Trees and shrubs		Various diseases
	Cherries	*Agrobacterium tumefaciens* *Pseudomonas*	*Coryneum* and *Polystigma*
	Shell nuts (walnuts, hazelnuts, almonds)	*Pseudomonas avellanae, P. syringae* pv. *coryli* *Xanthomonas campestris* pv. *juglandis*	
	Kiwi	*Pseudomonas syringae* pv. *actinidiae*	
	Olives	Olive knot (*Pseudomonas savastanoi*)	Olive peacock spot (*Spilocaea oleaginea*), *Fusicoccum*
	Peach (+ apricot)	*Xanthomonas arboricola* pv. *pruni* *Pseudomonas*	Peach leaf curl (*Taphrina deformans*), Peach canker (*Fusicoccum* sp.) *Coryneum* and *Polystigma*
	Apples (+ pears, quince, Asian pear)	*Pseudomonas*	European canker (*Nectria galligena*) Foliar diseases Scab (*Venturia inaequalis*)
	Plum	Bacterial diseases	Scab(s) Leaf curl
	Black currant		Foliage diseases
	Raspberry		Foliage diseases
	Grapes	Crown gall (*Agrobacterium vitis*)	Phomopsis cane and leaf spot (*Phomopsis viticola*) Downy mildew (*Plasmopara viticola*)

Table 1.1. Next

	Crops	Diseases/pathogens	
		Bacterial diseases	Fungal diseases
Arable field crops	Wheat		Fungi other than Pythiaceae [seed application]: Common root rot (*Bipolaris sorokiniana*), Take-all (*Gaeumannomyces graminis*), Fusarium moulds (*Fusarium graminearum*, *F. culmorum*, *Microdochium nivale*)
	Rye		Fungi other than Pythiaceae [seed application]: Fusarium moulds (*Microdochium nivale, Fusarium* sp.)
	Potato		Late blight : *Phytophthora infestans*
Vegetable crops	Artichoke	Bacterial diseases	Downy mildew(s)
	Carrots		Oomycete pathogens (Pythiaceae)
	Celery	Bacterial diseases	
	Chicory - root	Bacterial diseases	
	Chicory - witloof	Bacterial diseases	
	Cabbage crops	*Pseudomonas fluorescens* (broccoli) *Xanthomonas campestris* pv. *campestris*	Downy mildew(s)
	Cucumber (+ pickling cucumbers, summer squash)		Downy mildew
	Strawberry	Bacterial diseases	Brown spot
	Beans	Bacterial diseases	
	Hops		Downy mildew
	Lettuce	Bacterial diseases	Downy mildew (*Bremia lactucae*)
	Melon	*Acidovorax citruli* *Xanthomonas campestris* pv. *cucurbitae*	Downy mildew
	Onion	*Xanthomonas axonopodis* pv. *allii*	Downy mildew
	Leak	*Pseudomonas syringae* pv. *porri*	Downy mildew
	Tomato	*Pseudomonas syringae* *Clavibacter michiganensis* *Pectobacterium* spp., *Dickeya* spp. *Ralstonia solanacearum* many *Xanthomonas*	Late blight (*Phytophthora infestans*)

Table 1.1. Next

	Crops	Diseases/pathogens: Bacterial diseases	Diseases/pathogens: Fungal diseases
Other uses	Indoor & balcony plants		Various diseases
	Rose		Fungal cankers
	Seed crops		Various diseases
	Seed crops – Beet (sugar and forrage)		Downy mildew
	Seed crops for PAMCP*, ornamental and vegetable crops		Downy mildew, white rust Rusts
	PAMCP*	Bacterial diseases	Fungal diseases (mildews)
	General application		Wound dressing

* PAMCP: perfume, aromatic, medicinal and condiment plants. In square brackets [ ]: applications other than aerial sprays. (sources: Ephy database and ITAB Guide 2017).

• In **perennial crops**, approved uses of copper include fungal and bacterial diseases affecting grapevines, stone fruits, pome fruits, and tree nuts. Copper treatments are also occasionally used against diseases for which they are not approved, including brown rot blossom blight in apricots and black rot in grapes.

• In **vegetable crops**, copper is approved against fungal and bacterial diseases of a dozen or so crops belonging to various botanical families.

• In **arable field crops**, approved uses of copper are limited to combating late blight in potatoes, and a few fungal diseases in wheat and rye that can be transmitted by seed.

• Finally, copper is approved against various fungal diseases affecting perfume, aromatic, and medicinal plants (PAMCP); ornamental species; and seed crops, and for diseases that develop on tree cuts.

Target pathogens

Pathogenic microorganisms targeted by the crop protection uses of copper belong to three major groups. Conditions for disease development and the methods available to fight these diseases depend on the biological characteristics of the different pathogen groups. The three groups are:

• **Fungi**, especially **Ascomycetes**. Ascomycetes are fungi capable of both sexual reproduction (producing perithecia, which overwinter in dead infected leaf material and from which ascospores emerge in the spring, leading to primary infections of new plant material) and asexual reproduction (producing conidia on above-ground plant parts; dissemination of the conidiospores cause secondary infections through the summer and fall);

• **Oomycetes**. Long considered to be related to the fungi, oomycetes have a life cycle somewhat similar to that of ascomycetes but are taxonomically very distinct from the true fungi. They are characterized by non-divided hyphae, a diploid genome, and spores that can be self-motile in water (zoospores);

Box 1.1. Major uses of copper

Some uses of copper, notably in OA, are considered "major" in terms of the land area involved, the economic importance of the crops to be treated, the yield losses occasioned by the target diseases, and/or the quantities of copper applied. Such uses are the focus of the greatest number of research studies and technical trials.

Grapewine downy mildew, caused by the oomycete *Plasmopara viticola*, is one of the two most serious diseases for this crop (the other is powdery mildew). Severely damaging and with a high epidemic potential, especially in areas with an oceanic climate, it requires a highly effective level of protection, in the absence of which harvests can be severely impacted or even entirely lost. Given the high degree of susceptibility of most grapewine varieties, controlling downy mildew with a contact product like copper requires numerous applications (up to 15 or more per year). Vineyards occupy approximately 782,700 ha in France (Agreste 2016).

Apple scab, caused by the ascomycete fungus *Venturia inaequalis*, is a disease of economic importance (scabbed fruit is unmarketable). Apple orchards receive an average of 23 applications of fungicides/bactericides per year (ranging from 15 to 29 depending on the region), nearly three-quarters of which target apple scab (Agreste). Copper can cause russetting on fruits, so the protection of organic apple trees against scab relies on a combination of copper (highly effective), sulfur, and lime sulfur (where permitted). Copper-based treatments are also used to control European canker (caused by Nectria galligena). Apple production for table fruit accounts for about 36,500 hectares in France.

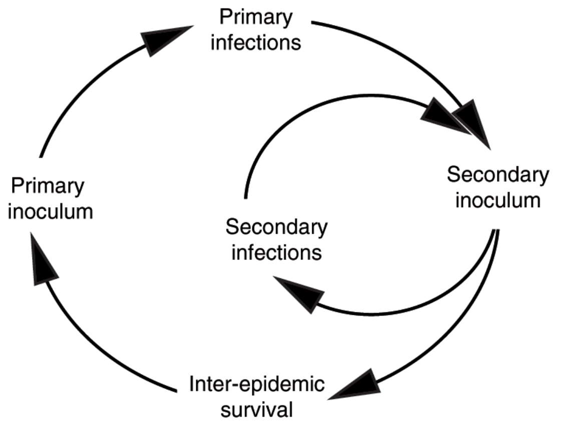
Potato late blight, caused by the oomycete *Phytophthora infestans*, is the most serious disease of potatoes. It manifests with symptoms of spreading necrosis on all plant parts (leaves, stems, and tubers), and can result in yield losses of up to 100 percent. In the case of late infestations, it can cause quality losses due to rotten areas on affected tubers. Potato late blight affects all areas of potato production, but is more regularly severe in oceanic climates. To control late blight, growers make an average of 10 to 12 applications of copper-based fungicides per year, or up to 15 to 20 in areas of high risk for late blight. Potato production accounts for approximately 180,000 ha in France.

P. infestans also causes serious damage to tomatoes (which belong to the same plant family as potatoes), particularly in field production.

- **Bacteria.** Prokaryotic organisms which in most cases rely on asexual reproduction, and which typically penetrate the plant *via* natural openings (stoma, lenticels, wounds) rather than by means of their own specialized structures.

These pathogens all have in common to generate polycyclic infections (Figure 1.2) and to depend upon liquid water (or at least saturating humidity) for the dispersal and germination of fungal spores (*sensu lato*) and bacterial dissemination.

Figure 1.2. Schematic life cycle of polycyclic fungal diseases.



Pesticides can inhibit the growth of non-reproductive tissues (hyphae) and/or the production and germination of spores (from sexual or asexual reproduction). Combating these polycyclical diseases requires beginning treatments as soon as weather conditions (rainfall, temperature) become favorable to primary infection in the spring, and continuing throughout the growing season as long as conditions are favorable to secondary infections. Existing decision-making tools (DMT) are intended primarily to optimize the timing of applications while limiting their total number. Such tools assess infection risks by using models to simulate pathogen development according to meteorological conditions.

Regulatory restrictions on the use of copper

Recognition of the negative environmental effects of copper-based products has led to regulatory restrictions on their use. In the EU, the copper re-homologation procedure of 2018 set the maximum dose of copper-based formulations allowed for crop protection purposes, both in organic and conventional production systems, at 4 kg of metal copper/ha/yr (down from to 6 kg/ha/yr before) as a 7 yr moving average. Rates recommended to producers by agricultural advisory services may be considerably lower than this maximum allowance. Furthermore, some countries have chosen to regulate copper more strictly. In Switzerland, applications are limited to 4 kg Cu/ha/yr for most crops (based on a sliding average over 5 years, with up to 6 kg permitted in the case of intense disease pressure in a given year); for small fruits, the maximum allowed amount is 2 kg/ha/yr; for stone fruits, 1.5 kg/ha/yr. Other countries (the Netherlands, Scandinavia) and some certification associations (Demeter in Germany, for example) have chosen to totally prohibit the use of copper for crop protection purposes, in both OA and in CA. The use of copper as