Org. Agr. (2020) 10 (Suppl 1):S159–S171
https://doi.org/10.1007/s13165-020-00330-2

SI: ORGANIC WORLD CONGRESS 2020

Check for updates

Current use of copper, mineral oils and sulphur for plant protection in organic horticultural crops across 10 European countries

N. Katsoulas · A.-K. Løes · D. Andrivon · G. Cirvilleri · M. de Cara · A. Kir · L. Knebl · K. Malińska · F. W. Oudshoorn · H. Willer · U. Schmutz

Received: 30 April 2020 / Accepted: 1 October 2020 / Published online: 7October 2020

Abstract The use of several plant protection inputs of mineral origin, such as copper, sulphur or mineral oils is seen as contentious by many consumers and stakeholders within the organic sector. Although the use of these inputs is legal in organic systems and also applied in non-organic agriculture, their use by organic growers raises questions for organic practice, which aspires to be free from toxic, non-renewable chemicals. Data on the current use of permitted plant protection inputs is currently scarce, especially in horticulture where chemical inputs deserve special attention since horticultural products are often readily edible. A mapping of the use of copper, sulphur and mineral oils was conducted by collecting expert knowledge across 10 European countries during May–October 2018, i.e. before the limitation of copper use to 4 kg ha^{-1} year^{-1} from February 1, 2019. Results show that copper is widely used by Mediterranean organic growers in citrus, olive, tomato and

N. Katsoulas (✉)
Department of Agriculture Crop Production and Rural Environment, Lab of Agricultural Constructions and Environmental Control, University of Thessaly, Fytokou Str., 38446 Volos, Greece
e-mail: nkatsoul@uth.gr

A.-K. Løes
Norwegian Centre for Organic Agriculture (NORSØK), Gunnars veg 6, N-6630 Tingvoll, Norway

D. Andrivon
INRA, Institut de Génétique Environnement et Protection des Plantes (IGEPP), Le Rheu, France

G. Cirvilleri
Department of Agriculture, Food and Environment (Di3A), University of Catania, Via S. Sofia, 100, 95123 Catania, Italy

M. de Cara
Instituto Andaluz de Investigación y Formación Agraria, Pesquera, Alimentaria y de la Producción Ecológica (IFAPA)-Centro La Mojonera, San Nicolás 1, 04745 Almería, Spain

A. Kir
Ministry of Agriculture and Forestry, General Directorate of Agricultural Research and Policies, Olive Research Institute, University Str., N.43, 35100 Izmir, Turkey

L. Knebl
Forschungsring e.V, Brandschneise 5, 64295 Darmstadt, Germany

K. Malińska
Institute of Environmental Engineering, Częstochowa University of Technology, Brzeźnicka 60a, 42-200 Częstochowa, Poland

F. W. Oudshoorn
Danish Agriculture & Food Council, SEGES, Agro Food Park 15, 8200 Aarhus, Denmark

H. Willer
Department of Extension, Training and Communication, Research Institute of Organic Agriculture–FiBL, Ackerstrasse 113, CH-5070 Frick, Switzerland

U. Schmutz
CAWR, Centre for Agroecology, Water and Resilience, Coventry University, Garden Organic, Ryton Gardens, Coventry CV8 3LG, UK

potato production. The annual limit of 6 kg ha^{-1} year^{-1} was not always respected. We also found that tomato producers apply high amounts of copper in winter crops in greenhouses. Mineral oils are applied to control scales, mites and whiteflies. Sulphur is also commonly used by organic vegetable growers, especially in greenhouses. We conclude that the high usage found in various different crops (especially Mediterranean crops) confirms the need for researching alternatives.

Keywords Mediterranean crops · Greenhouse crops · Tomato · Contentious inputs, plant protection

Introduction

Organic farming has enjoyed a rapid and significant growth in many European countries since EU regulations for organic production were first established in 1991 (EEC 1991), and subsequently revised in 2007 (EC 2007), 2008 (EC 2008a, b) and 2018 (EU 2018; to be implemented as of January 1, 2021). During these 20 years, organic farming in Europe has grown from a small niche to a major industry, covering more than 15 million hectares.

According to statistics compiled by the Research Institute of Organic Agriculture, FiBL (Willer et al. 2020), the majority of organically managed land worldwide is permanent grassland (67%), followed by arable land (19%) and perennial crops (7%). In Europe, the majority of organically managed land is arable land (48%), followed by permanent grassland (40%) and perennial crops (11%). European organic arable land, perennial crops and permanent grassland amounted in 2018 to 1.1%, 2.9% and 1.5% of the world's arable land, perennial crops and permanent grassland, respectively.

In Europe, the nine organically grown commodities covering the largest proportion of land in 2018 (excluding cereals) were olives, dry pulses and protein crops, oilseeds, grapes, nuts, vegetables, fruits, root crops and citrus (Fig. 1). Organic cereals were grown on about 2.64 million ha in 2018.

Worldwide, more than 872,000 ha of olives, 90,000 ha of citrus fruits and 387,000 ha of vegetables were grown organically in 2018. As shown in Fig. 3, about 70% of organic olives, and 50% of citrus and vegetables are grown in Europe. Olives are mainly grown around the Mediterranean Sea, with Tunisia being the major producing country, followed by Italy and Spain. Turkey and Greece are also important producers. For citrus, the largest organic producer is Italy with nearly 36,000 ha, constituting 24% of Italy's total harvested citrus fruit area, followed by Spain with 14,000 ha comprising 5%. Italy is also number two among the world's producers of organic vegetables (Fig. 2), and France is also a leading country for organic vegetables.

All products labelled as organic and sold in the EU must be produced in accordance with EC (EC 2007; EC 2008a, b) and EU (EU 2018) regulations, which are also important since they influence organic production even outside the EU. The legal status of contentious inputs is a key element in the regulatory and legislative framework of organic agriculture. Indeed, some inputs were seen as contentious but absolutely needed when the first basic standards of IFOAM Organics International were

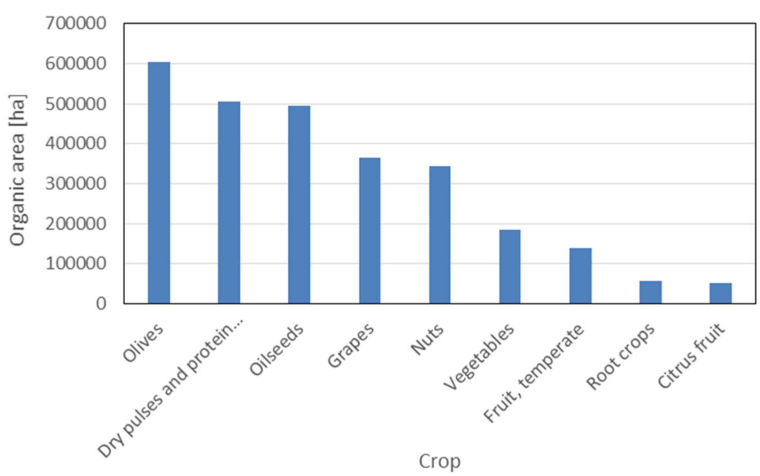

Fig. 1 Area covered by the nine organic farming commodities that correspond to the largest organic area in Europe. Cereals cover the largest organic farming area in Europe (about 2.64 million ha). (Source: Willer et al. 2020)

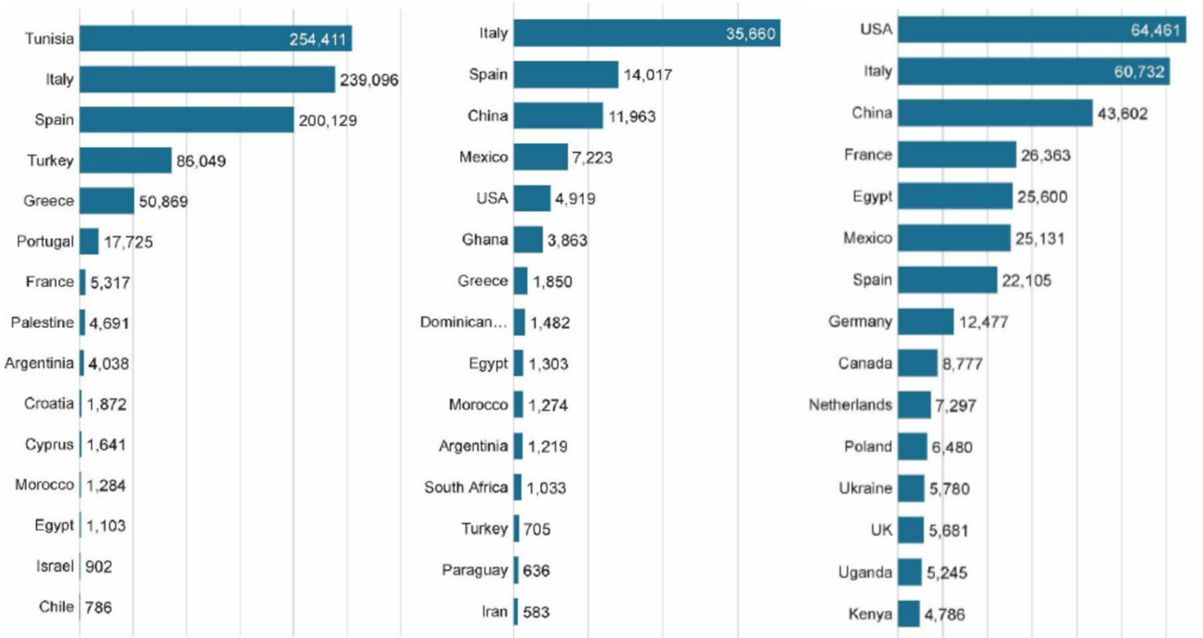

Fig. 2 Countries with the largest organic area (in ha) worldwide in olives (left), citrus (center) and vegetables (right) (source: Willer et al. 2020)

established (Anonymous 1982). Among these are several plant protection products against pathogens or pests, such as sulphur and copper salts which were permitted for use when required for plant disease management, whereas mineral and paraffin oils were allowed for pest management (Table 1). When the EU started to make regulations for organic production, the basic standards of IFOAM were an important source of information. The current legal status for the use of copper, sulphur and mineral oils in the EU is ruled by the European Commission (EC) regulation no 889/2008 of 5 September 2008. The regulation in EC (2014) (Table 1) related to the use of copper in organic production set the yearly maximum limit at 6 kg Cu ha^{-1}. In perennial crops, more than 6 kg copper per hectare and year may be applied by derogation in one given year, provided that the average quantity actually used over a 5-year period consisting of that year and the four preceding years does not exceed 6 kg. On November 27, 2018, the European Commission voted on the future of copper in European

Table 1 Substances permitted since the first IFOAM basic standards for traditional use in organic farming (EC 2014)

Name	Description, compositional requirement, conditions for use
Copper in the form of copper hydroxide, copper oxychloride, (tribasic) copper sulphate, cuprous oxide, copper octanoate	Fungicide up to 6 kg Cu ha^{-1} year^{-1} For perennial crops, Member States may, by derogation from the previous paragraph, provide that the 6 kg copper limit can be exceeded in a given year provided that the average quantity actually used over a 5-year period consisting of that year and of the four preceding years does not exceed 6 kg
Sulphur	Fungicide, acaricide, repellent
Lime sulphur (calcium polysulphide)	Fungicide, insecticide, acaricide
Paraffin oil	Insecticide, acaricide
Mineral oils	Insecticide, fungicide; only in fruit trees, vines, olive trees and tropical crops (e.g. bananas)

agriculture, and decided to lower the limit to 4 kg Cu ha^{-1} $year^{-1}$ counted as an average over a 7-year period (in other words, maximum 28 kg Cu ha^{-1} over 7 years). These new rules have been enforced since February 2019, although some countries (like France) have opted for a flat 4 kg ha^{-1} $year^{-1}$ rate, without compensations between years. The dose reduction decided in 2018 opens the way for future regulatory restrictions on copper use after 2026, which may decrease the permitted dose below the current 4 kg Cu ha^{-1} $year^{-1}$ and to less than 28 kg Cu ha^{-1} in 7 years.

However, both copper and sulphur are toxic to insects, and especially to the soil fauna and beneficial soil microbiota (Kandeler et al. 1996). Copper is also toxic to many aquatic organisms (Solomon 2009), markedly increases the development of copper-resistant bacterial strains (Aiello et al. 2015; Benlau et al. 2012) and tends to accumulate in soils during prolonged use, sometimes to phytotoxic concentrations (Deng et al. 2009; Hippler et al. 2018). The toxicity of sulphur to arthropods, including beneficial species, could affect the efficacy of biological control (e.g. Zappala et al. 2012). Provided that pure paraffin oil is used, the application implies no risk for growers and consumers (EFSA 2008). However, paraffin oil is highly toxic for aquatic organisms, and toxic for bees (EFSA 2008).

To address the issues related to copper use for plant protection in organic or conventional systems and search for alternatives, the EC funded over the years successive research projects (e.g. CO-FREE, Blight-MOP, REPCO) aiming at reducing or replacing copper use in major crops, in particular potatoes, grapes and apple. At the same time, national funding bodies also supported several projects on the same topic. In the latest of these projects, Schmitt (2016) concluded that a range of measures that were developed in the frame of the CO-FREE EC funded project were ready to be implemented, while others needed further development; for example, for several of the alternative compounds investigated, the earliest registration is likely to be completed from 2022 only. Also, new varieties need time to be adopted by farmers, retailers and consumers, and communication and commitment along the whole value chain is essential. These results indicated that strategies including the use of alternative compounds as one component together with DSS and further measures should be the way forward to further reduce/replace copper. However, the replacement and reduction of copper are currently slowed down beyond the technical potential by, for example, the legal frameworks, associated costs or lack of markets.

Sulphur and mineral oils have until now not been subjected to comparably comprehensive research efforts, but their efficacy and negative impacts are being discussed and it is questioned whether these pesticides are actually better than synthetic pesticides (Bahlai et al. 2010).

In spite of the mentioned research efforts, copper and several other contentious inputs are still widely used by European organic growers. This is why the Organic PLUS project aims to provide scientifically informed decision support to assist policy makers on EU, national and regional level in phasing out contentious inputs from organic production across Europe. The project more specifically targets, among others, the use of plant protection inputs (copper, sulphur, mineral oils etc.) in horticultural crops.

The project activities started by mapping the current use of contentious inputs across Europe as a basis for developing alternatives. This paper reports on the mapping data generated within Organic PLUS for the plant protection products (copper, sulphur and mineral oil) currently allowed but contentious in organic crops, with a focus on horticultural productions. This mapping will serve as a basis for evaluating the need for alternatives to these contentious inputs.

Methodology

To achieve a comprehensive overview of the current use of and need for external inputs, we carried out a mapping activity in 2018 (Katsoulas et al. 2018). Since the use of inputs is highest in horticulture, the mapping concentrated on the most important organically grown horticultural crops in each country. For this purpose, an open-type questionnaire was developed and used (Table 2). The questionnaire included also questions related to the methods, practices and products used in practice by the growers as alternatives to or for reduction of the use of contentious inputs for plant protection in organic farming.

To complete the survey, expert knowledge and a per-crop approach was used. Information was received from one to three experienced advisors and/or farm managers and organic certification bodies per crop and country, for 14 crops in 10 countries (Table 3). Each questionnaire therefore represents the input from several actors.

Table 2 Questionnaire used for the collection of information related to contentious inputs use for crop protection in organic farming

-Region to which the information applies
-Crop
-Dominating varieties
-Propagation material
-Soil type, cultivation system and crop rotation. If under cover indicate the type of typical structure
-Fertilization: indicate the calendar the type and quantities (per year and unit land area) of fertilizers and manure used
-Crop protection: indicate the type and quantities of crop protection products used with special reference to copper, mineral oils and sulphur used per year and unit land area
-What is a typical/representative yield level? (kg ha^{-1})
-Alternatives used for crop protection/comments

The crops selected are important organic crops in the respective country. In total, 68 questionnaires were obtained, relating to the following crops: apple, broccoli, cabbage, carrot, citrus, cucumber, eggplant (aubergine), lettuce, olive, potato, pepper, strawberry and tomato (Table 3). Quantitative data were averaged per crop and country, while the qualitative text data were summarized per crop and country.

Results

Copper inputs

In 8 out of 10 countries surveyed, copper-based products have been permitted as bactericides and fungicides for plant protection and in organic growing since 1994. In Norway, the use of copper was not permitted for organic growing until March 2017, when the EC regulation 834/2007 was fully implemented. However, the national limit for copper use in agriculture in Norway is 4 kg ha^{-1} $year^{-1}$; thus, it is easier for these growers to comply with lower limits of copper from 2019. By September 2018, copper use in Norway was reported only in apples, in amounts less than 4 kg ha^{-1} $year^{-1}$. By the time of the study, many farmers and even advisors were still not aware that such use was permitted since 2017.

In Denmark, copper is not applied as a pesticide in organic growing because national authorities have not (yet) been asked to approve any commercial product containing copper, or have not approved it. The use of

Table 3 Overview of crops and countries where information about contentious inputs was recorded. The numbers indicate how many informants have filled in a table of information for each crop

Crops/countries	Apple	Broccoli	Cabbage	Carrot	Citrus	Cucumber	Aubergine	Lettuce	Olive	Potatoes	Pepper	Strawberry	Tomato	Sum
Denmark	1	1								1		1	1	5
France				1			1	1	1	1			4	9
Germany			1							1			1	3
Greece	1	1			1				1	1			1	6
Italy					3				2	2			2	7
Norway	1			1						1		1	1	5
Poland						1				1		1	1	4
Spain					3				3				3	9
Turkey					1		1		1	1	1	1	1	7
UK	2	2	2	2				1				1		8
Sum	5	4	3	4	8	1	2	2	8	9	1	5	15	68

copper in Denmark is forbidden also for conventional growers. However, since copper is also an essential micronutrient for plants, if there is evidence for copper deficiency, and a certified organic advisor reports the deficit, copper fertilizer as leaf sprays may be used. Such use of copper as a micro-nutrient may actually also work as a masked plant protection measure.

In the following sections, details on copper use in olives, citrus, vegetables and potatoes are given.

Olives

In France, olive growers use copper in the form of Bordeaux mixture with 2 to 3 applications per year, which result in a total Cu dosage of 5 kg ha^{-1} $year^{-1}$. In Greece, depending on (i) the weather conditions in particular areas, (ii) grower's knowledge and (iii) cultivar sensitivity (cultivars 'Kalamata' and 'Chondrolia' are more sensitive to disease than 'Conservolea'), growers apply between 1 and 6 kg Cu ha^{-1} $year^{-1}$ (Fig. 3).

In Italy, the dry weather conditions in Sicily and the existing resistant olive varieties allow for only 1 or 2 applications per year of copper oxychloride, whereas in Calabria, the main cultivated variety (*Carolea*), which is susceptible to *Colletotrichum gloeosporioides*, *Spilocaea oleagina* and *Pseudomonas savastanoi*, and the comparatively rainy weather prompt a higher number of copper applications (up to 8 per year). The average copper use in olives in Italy ranges from 1.8 to 6.0 kg ha^{-1} $year^{-1}$.

In Spain, copper is usually applied in olives once or twice a year (spring and autumn treatments), but one more autumn treatment can be carried out in wet years. Total copper quantities applied can vary from 4.2 to 6.3 kg ha^{-1} $year^{-1}$. Irrigated crops can afford the cost of treatments. Without irrigation, it is quite common to completely avoid fungicide applications. In Turkey, due to moderately sloping land that makes the use of machinery for spraying applications difficult and to the dry climate, at least 80% of olives under organic farming management are grown without any copper inputs.

Citrus

The copper use in different countries in organic citrus production is summarized in Fig. 4. In Greece, copper is used in *Citrus* against *Phytophthora* spp., *Alternaria* spp. and *Colletotrichum* spp., as 1–2 applications per year according to the weather conditions and the infection intensity, for an average amount of copper of 1–3 kg ha^{-1} $year^{-1}$.

In Italy, orange and mandarin are sprayed once or twice a year with copper oxychloride, the total number of applications depending on rainfalls. The average copper amount sprayed ranges from 2.5 to 4.1 kg ha^{-1} $year^{-1}$, with main indications against *Phytophthora*, *Colletotrichum*, *Alternaria* and *Pseudomonas*. In lemons, depending on annual climate, 2 to 4 applications per year of copper oxychloride or hydroxide are used (4.0 to 8.0 kg ha^{-1} $year^{-1}$). The number of applications depends on rainfalls, wind-driven rainfalls and hail showers (which cause wounds favouring the infection by *Plenodomus tracheiphilus*).

In Spain, copper in citrus production is normally applied once during the winter, that means a copper

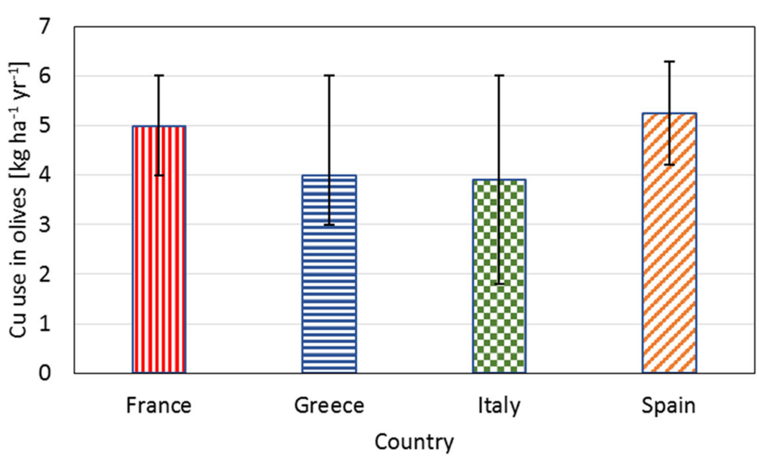

Fig. 3 Copper use in different countries in organic olive production (in kg ha^{-1} $year^{-1}$). The error bars represent the range of Cu inputs within countries

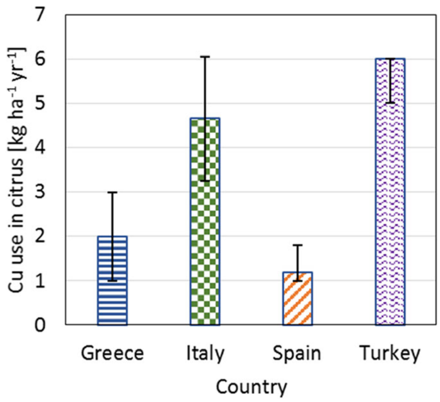

Fig. 4 Copper use in different countries in organic production of citrus. The error bars represent the range of Cu used

amount of about 1.2 kg ha^{-1} year^{-1} if the highest concentration of copper oxide (75% Cu) is used.

In Turkey, copper sulphate and Bordeaux mixture are used in citrus to control *P. tracheiphilus* and *Phytophthora* spp. with an application rate of 6 kg ha^{-1} year^{-1}.

Tomato

The copper use in different countries in organic tomato production is presented in Fig. 5. In tomato and other vegetables, copper is used as a preventive fungicide, but is also applied as soon as the first symptoms of diseases appear. Some growers use the maximum dose (4 to 6 kg ha^{-1} year^{-1}) in a single pass, whereas fractionation at 400 g ha^{-1} is recommended for the first passages (in the absence of disease).

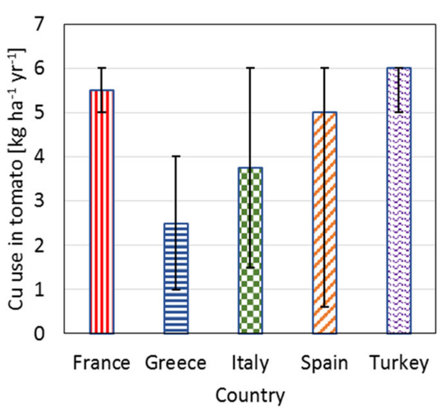

Fig. 5 Copper use in different countries in organic production of tomato. The error bars represent the range of Cu used

In Greece, organic tomato is cultivated in greenhouses with adequate climate control, which can ensure acceptable levels of temperature all year round. The number of yearly applications against *Xanthomonas* spp. and *Pseudomonas* spp. may vary between 4 and 10 (1–4 kg ha^{-1} year^{-1}), according to outside weather conditions (and accordingly internal, greenhouse environment) and infection intensity. In France, the use of copper is close to the limit of 6 kg Cu ha^{-1} year^{-1} in most tomato production. Standard schedules usually involve three applications of Bordeaux mixture (5 kg Cu ha^{-1} year^{-1}) between planting and early harvest. Extra 'curative' applications (up to 4 year^{-1}) may include copper hydroxide if symptoms of *Phytophthora infestans*, *Cladosporium cladosporioides*, *Botrytis cinerea* or *Alternaria solani* are seen. In Sicily (Italy), organic tomatoes are generally grown in greenhouses with 3 to 8 applications per year of copper hydroxide, for an average copper use ranging from 1.5 to 6.0 kg ha^{-1} year^{-1}. The number of copper applications, mainly against *Phytophthora infestans*, *Xanthomonas* and *Pseudomonas*, depends on air humidity inside the greenhouses. In Spain, open-field tomato crops (Northern Spain) use 0.5 kg Cu ha^{-1} year^{-1} in the form of copper oxychloride. In greenhouses (South-Eastern Spain), the consumption of copper is being reduced due to the substitution of classic copper formulations by copper gluconate that contains only 6% Cu. The main tomato cycle in greenhouses is conducted in winter, so in this case copper is applied 2–5 times, resulting in a maximum of up to 0.6 kg Cu per hectare and growing cycle. However, still many growers using classic copper formulations reach a maximum consumption of 6 kg ha^{-1} year^{-1} (e.g. 4 applications of copper oxychloride (75%)). In Turkey, copper is applied to tomato as copper sulphate and Bordeaux mixture at 6 kg Cu per hectare and year.

Other vegetables and potatoes

In Greece, copper is applied (1–2 kg ha^{-1} year^{-1}) to control *Alternaria brassicae* and *Peronospora brassicae* in broccoli. In Germany, asparagus, onion and carrot growers apply from 1 to 2 kg Cu ha^{-1} year^{-1}. In Turkey, copper is applied to pepper and eggplant as copper sulphate and Bordeaux mixture at 6 kg Cu ha^{-1} year^{-1}.

The main reason for Cu application in potato is to control *Phytophthora infestans*. The data collected in

France for potatoes indicate that the average use of copper is about 4 kg Cu ha^{-1} year^{-1}, but with strong discrepancies between regions and growers. Potato growers in coastal areas of the northern half of France apply up to 6 kg Cu ha^{-1} year^{-1} due to the environmental conditions (high humidity and moderate temperatures, favouring late blight infections). In Germany, the typical amount of copper applied in potato is between 1.4 to 1.9 kg ha^{-1} year^{-1}, with some farms applying up to 3 kg and others no copper at all. In Greece and Italy, Cu applications on potato reach on average 5–6 kg ha^{-1} year^{-1}, with 6–8 applications per year according to the weather conditions and the infection intensity. In Sicily (Italy), organic potatoes are grown during two different periods: early seeding in September and late seeding in January, to avoid infections of *Phytophthora infestans* at an early stage of crop growth. Up to 12 applications of copper per year are performed, using either copper oxychloride or hydroxide and resulting in a year-round copper use that highly exceeds the limit of 6 kg ha^{-1} year^{-1}. In the UK and Poland, copper is used in the form of copper oxide or oxychloride at a rate of 2.5–3 kg ha^{-1} year^{-1}. Many small-scale farms, and also larger farms, use no copper inputs in potato.

Mineral oils inputs

Not many quantitative data could be obtained about the use of mineral oils. Nevertheless, the limited data acquired show that in some situations (e.g. in citrus), mineral oils can be considered as the main contentious input.

In Italy, mineral oils are applied to control scales, mites and whiteflies in citrus and olive orchards and occasionally in tomato. In citrus, they are usually applied once or twice per year, with an average quantity of 30 to 100 l ha^{-1} year^{-1}. In olives and tomato, the average mineral oil use is up to 30 and 10 l ha^{-1} year^{-1}, respectively. In other crops, they are of minor use or concern, and can in any case be easily replaced by plant-based oils.

In France, mineral oils are used in seed potato to prevent attacks by virus-transmitting aphids. By 2018, all organic seed potato growers in France have replaced mineral oils by organic oils of plant origin, mainly oilseed rape. In Norway, the use of mineral oil became permitted in 2017. Only one commercial product containing paraffin oil is available, which was approved after 2018. The main recommended use is against aphids in (seed) potatoes, to avoid spreading of virus (max. 1 application in 3 years). It may also be used in fruits against various insects such as mites, aphids and pear psyllid (*Cacopsylla pyri*) once per year, at a rate of 10–20 l ha^{-1} year^{-1}.

In Germany, paraffin oil is used by about 10% of the Demeter Association growers to fight red spider mite, but is not allowed within the Naturland Growers Association. Paraffinic oil is applied sporadically (1–2 applications) in organic greenhouses with tomatoes in Spain. This product is not compatible with sulphur, which limits its use. The maximum application would reach less than 13 l ha^{-1} year^{-1}. Mineral oils are rarely used in olives in Spain while in citrus, their use is high due to the wide spectrum of the product. A maximum of 90 l ha^{-1} year^{-1} of (54%) product is applied, i.e. approximately 50 l ha^{-1} year^{-1} of paraffinic oil.

In Denmark, Greece and UK, no use of mineral oils was reported. This does not mean they are not used at all, but most likely only very little. The use of paraffin oil is permitted by EU regulations as preventive acaricide and insecticide to horticultural crops. There is no maximum level restriction for the amount of mineral oils to be used per hectare and year, but for the studied crops, it is considered that a reduced use is currently manageable.

Sulphur inputs

Sulphur is very commonly used by organic vegetable growers, especially in greenhouses. It is a repellent to pests, killer of mites, and effective against powdery mildews. Sulphur use can range between 10 and 100 kg ha^{-1} year^{-1} depending on the production system and the incidence of pests.

In Norway, sulphur is the most commonly applied commercial pesticide in organic crops. It is used in apples, strawberries and tomatoes, but not potatoes or carrots. It was permitted for organic growing in Norway when the first regulations were introduced, in 1991, and is still permitted with no maximum limit as to the dose per hectare and year. Currently, only one commercial product containing elementary sulphur is available, called Thiovit Jet (Syngenta). This is ground elementary sulphur (80%) mixed with compounds facilitating application in field and adhesion to plant organs. The applied doses vary according to crops, but are highest in strawberries, where the suggested ones are up to 7.5 kg ha^{-1} each 10–12 days from early spring to flowering, and after harvest. Other berries are more sensitive, and a maximum of 3–4 applications per year is recommended, with 4.5–7.5 kg ha^{-1} per application. In fruit, 1–3 applications before flowering are recommended, with doses up to 12 kg ha^{-1} per application.

In France, sulphur is used against some fungal diseases (mainly powdery mildews) and as an acaricide against spider mites. Its use in tomato is very occasional, and very rare in eggplants where black soap is preferred. In Greece, sulphur is used in tomato as 2–3 applications up to flowering with an average rate of 2.5–5 kg ha^{-1} year^{-1}, according to the infection intensity (pathogens and mites). It is also used in olives against leaf-feeding insects, at a rate of 15–20 kg ha^{-1} year^{-1}, depending on insect pressure.

In Italy, sulphur is used as a fungicide in tomato crops, and sporadically as an insecticide or acaricide in citrus orchards and potato crops; it is not used at all in olive orchards. Sulphur is normally applied as sulphur proteinate (45% sulphur) at rate of about 3.5 kg ha^{-1} year^{-1} to control of scales and mites. It is important to note that in recent years, the use of *Citrange* spp. in place of sour orange as rootstock triggered the use of sulphur, as a powder, to correct soil pH. For this purpose, 400 kg ha^{-1} year^{-1} of sulphur is used. Sulphur in Italy is also used 1–2 times a year at an early stage of tomato growth in absence of bumble bees in the greenhouses, and 2.5–5 kg sulphur per hectare and year is applied to control mites and pathogens. Finally, in potato, sulphur compounds are combined with copper to reduce the inputs of copper.

Sulphur is also used in high amounts in tomato greenhouses in Spain. Its main targets are powdery mildews and tomato russet mite, but it is also applied as a powder formulation to repel whiteflies. Powdered sulphur can be applied up to 3 times (25 kg ha^{-1} per application), followed by up to 4 treatments with pulverized sulphur (80% maximum richness) per cycle depending on environmental conditions. This is, in the highest case, a total of 95 kg ha^{-1} year^{-1}. This extreme is sometimes reached in tomatoes cherry or cocktail types, because these tomatoes are washed with water before packing (so sulphur is removed). Conventional greenhouse growers apply about 30% less sulphur than organic, and substitute sulphur by synthetic fungicides. In open fields, there is a typical consumption of 10–12 kg ha^{-1} year^{-1} powdered sulphur (98%). It is worthy to mention that in Spain, the use of powdered sulphur is only allowed in open fields since 2019, i.e. after this survey was carried out.

In Turkey, it seems that it is traditional to use sulphur twice a month at the beginning of transplantation seedlings to the open field in tomato, pepper, eggplant and strawberry even if pathogen was not determined in both open field and greenhouse production.

Alternatives to copper

Alternatives to copper currently in use by growers in citrus, olives, tomato, eggplant and potato include:

- Low-copper-grade formulations, with reduced copper content (2–6%) and which allow a smaller amount of copper to be applied per hectare;
- Inorganic substances: potassium salts (potassium hydrogen carbonate, K_2SiO_3), lime-sulphur used as a spray to control fungal infections with some effect on insects and bacteria; sprayable zeolite and kaolin for abiotic stress protection and olive fruit fly protection;
- Natural alternative formulations, applied to replace or reduce copper dosage, used alternately or in combination with copper. Some of them are included in Annex II to EC (2008a, b), permitted for plant protection in organic crop production;

– Plant extracts with biocidal properties and/or which stimulate plant defences;
– Essential oils: commercial formulations of citrus essential oils are approved for use in organic systems;
– Herbal preparations, including decoctions of nettle (*Urtica dioica*) and horsetail (*Equisetum* spp.).
– Compost/compost teas: compost tea, vermicompost and vermicompost tea.

- Biological control agents with a variety of mechanisms of action against fungal and bacterial pathogens which have a stimulating effect on plant defences. *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Pseudomonas* spp., *Trichoderma* spp., *Pythium oligandrum* and *Streptomyces* spp., are examples of BCAs currently available to growers.
- Plant defence stimulators, such as chitosan, a natural polymer derived from chitin, reported to be directly effective against a variety of microorganisms and to stimulate plant defence mechanisms, or seaweed extracts (*Ascophyllum nodosum* and *Laminaria digitata*) Laminarin extracted from *L. digitata* does not have a bactericidal or fungicidal effect, but enhances plants' resistance to pathogens.

- A number of resistant cultivars are available, for all market segments. Their resistance comes from different physiological mechanisms, and can be highly effective in a wide range of environments, but is not always durable.

Alternatives to mineral oils and sulphur

The results of the survey showed that the usual substituent for mineral oils is plant oils (e.g. from rapeseed), in particular in seed potato production. The substitution provides a satisfactory efficacy, organic and mineral oils having a similar performance in preventing insect-borne viral transmission. It should however be noted that organic oilseed rape production is scarce, and that some growers report efficacy limitations with plant oils compared with mineral oils. The wide spectrum of effectiveness of mineral oils makes them more versatile than other alternatives which currently include:

- Soft potassium soaps (potassium salts of fatty acids)
- Zeolite, kaolin and diatomaceous earth
- Plant defence stimulators
- Biological control agents, in the form of predators or parasitoids of insects and mite pests: *Aphytis melinus*, *Cryptolaemus montrouzieri*, *Leptomastix dactylopii*, *Amblyseius andersoni*, *Neoseiulus californicus*, *Phytoseiulus persimilis*

Alternatives to sulphur are not currently applied, mainly for economic reasons since sulphur is cheap compared with other compounds. Moreover, since sulphur can be an alternative to mineral oils used to control insects and mites in citrus and olive orchards and occasionally in tomato, its use is not easily reduced.

Discussion and conclusion

Data on the current use of legal but contentious plant protection inputs in organic systems are currently scarce, especially in 'minor crops' such as horticulture which are less commonly surveyed but generate readily edible products. The mapping conducted within Organic PLUS and reported here partly fills this gap, by offering synthetic data on the use of three important types of active ingredients (copper, sulphur and mineral oils) over a range of countries and crops.

The data were collected in a participatory way, by synthesizing expert knowledge (organic certification bodies, horticultural advisors, growers) with a semi-structured questionnaire. This method allowed to rapidly generate the data corpus, but also to involve a wide range of actors, countries and crops. Therefore, and despite the apparently limited number of questionnaires generated, the data offer a consolidated appraisal of the extent and distribution of these contentious uses in European horticulture. It is reassuring that the data obtained in potato match quite well with a similar survey conducted almost two decades ago on copper use (Tamm et al. 2004), which validates the method and contents of the current survey.

Copper is still the most contentious input for plant protection in organic farming in Europe. By comparison, sulphur and mineral oils are currently under less scrutiny than copper, although their contentious status is also clear for toxicological reasons (especially their negative impact in insects) and, at least in the case of copper and mineral oils, because of their mode of production (oil chemistry from fossil, non-renewable hydrocarbures; chemical synthesis of non-native preparations in the case of copper). It is somewhat surprising that sulphur, which is toxic to arthropods (including pollinators) and has no legal application limits, is seldom considered problematic, except as a main component of sulphites in wine production. However, it is not selective, and it has harmful effects on beneficial insects and mites. So the use of sulphur can limit biological control and be very negative for bees, bumblebees and beneficial arthropods (Efrom et al. 2012; Ndakidemi et al. 2016; Gesraha and Ebeid, 2019).

For crops like citrus and olives, the former limit of copper quantities allowed (6 kg ha^{-1} $year^{-1}$) was not always respected. Mediterranean tomato producers also apply high amounts of copper in winter crops (greenhouses). This high and widespread use confirms the need for developing alternatives, especially in the current dynamics of progressive reduction of legal maximum limits. Certification bodies need to audit these crops carefully, so as to make sure that the new, lower, EU copper limits of 4 kg ha^{-1} $year^{-1}$, with no more than 28 kg ha^{-1} over the next 7 years (2019–2015), are indeed met.

Vittersø et al. (2019), who carried out a parallel survey on public opinion in Europe regarding contentious inputs as an activity within the Organic PLUS project, reported that Cu is in the second position (after antibiotics) of inputs considered contentious by the public, while mineral oils are in the fifth position (synthetic vitamins and plastic packaging are 3rd and 4th, respectively). Their survey also showed that, in all countries, a large number of respondents are in favour of stricter regulations on the use of copper. Especially, more than half of the respondents in Italy and Spain support this solution. As much as one-third of the Polish respondents want to ban the use of copper and also one in four in Germany, France, Italy and Spain are in favour of banning the use of copper altogether. Norwegians and British respondents are less inclined to completely ban copper use, and here more respondents than in the other countries (17 and 16% respectively) think that one can continue with the same use as today. However, as much as 17% of the total sample answer 'do not know' to this question, and again the Norwegian (28%) and UK (22%) respondents are those with the highest scores. These results confirms also the fact that copper is less used as an input in these countries, while in southern European countries, the use of copper to a greater extent are viewed as an environmental/food safety issue. The report of Vittersø et al. (2019) also presents that frequent organic buyers have greater willingness to pay more for Cu free products, but this willingness decreases in less-frequent buyers.

Phasing out such contentious inputs from organic agriculture is usually not straightforward. It requires a dedicated effort both from consumers, advisors and farmers and growers, who are often under economic pressure and adverse towards further change of organic regulations.

The alternatives to copper used by the respondents of the survey could be grouped, according to their underlying mode of action, in three main categories, as given by Andrivon and Savini (2019): (a) Methods that act directly on the pathogen itself. These include not only the application of biocidal substances (primarily plant extracts with antimicrobial properties) but also the use of biocontrol organisms that act directly on the pathogen through antagonism: antibiosis, hyperparasitism or ecological competition. (b) Methods that make use of plants' own capacity for resistance such as the development of resistant varieties, exploiting the genetic resources of the cultivated species or related species; the application of plant defence stimulators. Plant resistance can indeed be constitutive, or it can be induced by infection or other external stimuli. However, only a few alternatives that could be grouped to and (c) Methods that use agronomic practices to fight primary infection (prevention) or secondary infections (avoidance). Prevention methods include the management of potentially infected crop material (gathering, shredding or burying of litter; selection of disease-free seeds and plants). Avoidance methods include covering crops to avoid contamination by airborne or splash-borne spores; reducing the time during which above-ground plant parts are exposed to moisture, to limit spore germination and infection; and minimizing damage to foliage and other plant parts, which can create entry points for pathogens.

While the questionnaire identified some solutions already available or used by growers (resistant cultivars, biocontrol methods, vegetable oils instead of mineral ones, decision support systems…), the frequent and abundant use of copper and, to a lesser extent, sulphur and mineral oils shows that these solutions are either not widely adopted or not fully satisfactory.

The clearest example for these difficulties is again copper. Many alternatives to copper are under development, but few are already available on the market, and fewer still are currently used by growers to any substantial extent (Andrivon and Savini 2019). Furthermore, zero-copper in plant protection cannot be achieved by a simple substitution strategy (for instance, replacing copper by biocontrol products); it requires a more or less profound reconstruction of the crop production system, including changing cultivars (to favour resistant ones), developing prophylaxis and sanitation measures, adjusting fertilization, etc. This requires an integrative approach, which is still under-developed. The increasing restrictions on the amount of copper continue to drive the recurrent demand for research on 'alternatives'. Although the questionnaire that forms the basis of this paper attempted to contribute detailed knowledge on use of alternatives in European organic horticulture, especially in Mediterranean crops, further research is needed also regarding how growers cope with the reduction from 6 to 4 kg ha^{-1} $year^{-1}$ in the most critical crops. There could also be unintended consequences by growers reverting to conventional production. We thus hope that this mapping review will assist in identifying research priorities and developing tailor-made recommendations for the practical implementation of these alternatives in specific crops.

Acknowledgments The authors are very grateful for the kind assistance of many organic farmers and advisors, willing to share their knowledge and experiences. We also thank the following: Amador, J., Antón, A., Azzaro A., Bertuglia A, Blackhurst D, Blogg H, Cetinel B, Colom G, Dróżdż D, García MC, Kacprzak M, Lorite I, Montemayor E, Mrowiec M, Nanos G, Raskin BL, Rayns F, Valleix S and Vatsanidou A for their valuable contributions in the collection of data of this survey.

Authors' contributions Overall research design, budgeting and project administration U.S., N.K., A-K.L. and D.A.; data collection, N.K., A-K.L, D.A.,G.C., M.C., A.K., L.K., K.M., FW.O., H.W. and U.S.; writing—original draft, N.K., A-K.L., D.A., G.C. and U.S.; writing—review and editing, N.K., A-K.L., D.A., G.C., M.C. and U.S.

Funding This work was carried out under the Organic PLUS project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 774340—Organic PLUS.

Data availability The datasets generated during and/or analyzed during the current study are available in the Organic PLUS project repository, online in Katsoulas et al. (2018) and in Katsoulas and Løes (2018).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethics approval All research followed the H2020 project ethical guidelines and approval in respective countries.

Consent to participate Not applicable.

Consent for publication All authors consent to publish this work.

Code availability Not applicable.

References

Aiello D, Ferrante P, Vitale A, Polizzi G, Scortichini M, Cirvilleri G (2015) Characterization of *Pseudomonas syringae* pv. *syringae* isolated from mango in Sicily and occurrence of copper-resistant strains. J Plant Pathol 97:273–282. https://doi.org/10.4454/JPP.V97I2.015

Andrivon D, Savini I (eds) (2019) Can organic agriculture cope without copper for disease control? Synthesis of the Collective Scientific Assessment report. Quae editions, Paris ISBN: 978–2–7592-3156-0. Available as epub (free) from https://www.quae.com/produit/1629/9782759231560/can-organic-agriculture-cope-without-copper-for-disease-control, Assessed April 15, 2020

Bahlai CA, Xue Y, McCreary CM, Schaafsma AW, Hallett RH (2010) Choosing organic pesticides over synthetic pesticides may not effectively mitigate environmental risk in soybeans. PLoS One 5(6):e11250. https://doi.org/10.1371/journal.pone.0011250

Behlau F, Canteros BI, Jones JB, Graham HJ (2012) Copper resistance genes from different xanthomonads and citrus epiphytic bacteria confer resistance to *Xanthomonas citri* subsp. *citri*. Eur J Plant Pathol 133:949–963. https://doi.org/10.1007/s10658-012-9966-8

Deng H, Li XF, Cheng WD, Zhu YG (2009) Resistance and resilience of Cu-polluted soil after Cu perturbation, tested by a wide range of soil microbial parameters. FEMS Microbiol Ecol 70:137–148. https://doi.org/10.1111/j.1574-6941.2009.00741.x

Efrom CFS, Redaelli LR, Meirelles RN, Ourique CB (2012) Side-effects of pesticides used in the organic system of production on *Apis mellifera* Linnaeus, 1758. Brazil Arch Biol Technol 55(1):47–53. https://doi.org/10.1590/S1516-89132012000100005

EFSA (2008) Conclusion on pesticide peer review regarding the risk assessment of the active substance paraffin oil (CAS 8042-47-5, chain lengths C18-C30, reliable boiling point range not available). EFSA Sci Rep 219:1–61 https://efsaonlinelibrarywileycom/doi/pdf/102903/jefsa2009219r Assessed April 28, 2020

European Council (EC) (2007) Council regulation (EC) no 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing regulation (EEC) no 2092/91. Official Journal L 189 of 20.7.2007. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=LEGISSUM:l21118&from=EN. Assessed 19 March 2020

European Council (EC) (2008a) Commission regulation (EC) No 889/2008 of 5 September 2008 laying down detailed rules for the implementation of Council regulation (EC) No 834/2007 on organic production and labelling of organic products with regard to organic production, labelling and control. Official Journal L 250 of 18.09.2008. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2008R0889:20100701:EN:PDF. Assessed 15 April 2020

European Council (EC) (2008b) Commission regulation (EC) No 1235/2008 of 8 December 2008 laying down detailed rules for implementation of Council regulation (EC) No 834/2007 as regards the arrangements for imports of organic products from third countries. Official Journal L 334 of 18.09.2008. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008R1235&from=EN. Assessed 15 April 2020

European Council (EC) (2014) Commission implementing regulation No 354/2014 of 8 April 2014 amending and correcting regulation (EC) No 889/2008 laying down detailed rules for the implementation of council regulation (EC) No 834/2007 on organic production and labelling of organic products with regard to organic production, labelling and control https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:JOL_2014_106_R_0004&from=EN. Assessed 13 April 2020

European Economic Community (EEC) (1991) Council regulation (EEC) No 2092/91 of 24 June 1991 on organic production of agricultural products and indications referring thereto on agricultural products and foodstuffs. https://eurlexeuropaeu/legal-content/EN/TXT/HTML/?uri=LEGISSUM:l21118&from=EN. Assessed 19 March 2020

European Union (2018) Regulation (EU) 2018/848 of the European Parliament and of the council of 30 May 2018 on organic production and labelling of organic products and repealing council regulation (EC) No 834/2007. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.150.01.0001.01.ENG. Assessed 19 March 2020

Gesraha MA, Ebeid AR (2019) Impact of sulfur dust application on the abundance of two important coccinellid predators in marrow fields. Bull Natl Res Cent 43:34. https://doi.org/10.1186/s42269-019-0060-7

Hippler FWR, Petená G, Boaretto RM, Quaggio JA, Azevedo RA, Mattos D (2018) Mechanisms of copper stress alleviation in Citrus trees after metal uptake by leaves or roots. Environ Sci Pollut Res 25:13134–13146. https://doi.org/10.1007/s11356-018-1529-x

IFOAM (1982) IFOAM-standards of biological agriculture for international trade and national standards, with restricted validity to 2 years. IFOAM Secretariat, Topsfield, Massachusetts

Kandeler E, Kampichler C, Horak O (1996) Influence of heavy metals on the functional diversity of soil communities. Biol Fertil Soils 23:299–306

Katsoulas N, Løes AK (2018) Tables describing the use of various inputs during organic growing of important horticultural and arable crops across Europe. Deliverables from the Organic PLUS project: pathways to phase-out contentious inputs from organic agriculture in Europe, Annex to Organic PLUS deliverables, no. D3.1 and D5.1, Version 1.1. Coventry University, Coventry, UK, https://organicplusnet.files.wordpress.com/2019/02/d3.1-o-current-use-of-contentious-inputs-wp-plant.pdf. Assessed 14 Sept 2020

Katsoulas N, Løes AK, Andrivon D, Cirvilleri G, de Cara M, Kir A, Knebl L, Malinska K, Oudshoorn F, Raskin B, Schmutz U (2018). Current use and legal status of crop protection inputs. Deliverables from the Organic PLUS project: pathways to phase-out contentious inputs from organic agriculture in Europe, deliverable, no. 3.1, version 1.1. Coventry University, Coventry, UK. https://organic-plus.net/. Assessed 15 April 2020

Ndakidemi B, Mtei K, Ndakidemi P (2016) Impacts of synthetic and botanical pesticides on beneficial insects. Agric Sci 7: 364–372. https://doi.org/10.4236/as.2016.76038

Schmitt A (2016) Innovative strategies for copper-free low input and organic farming systems. Final Report Summary - CO-FREE. CORDIS EC, Grant agreement ID: 289497, https://cordis.europa.eu/project/id/289497/reporting. Assessed 15 Sept 15 2020

Solomon F (2009) Impacts of copper on aquatic ecosystems and human health. Environ Commun. January 2009, 25–28. http://www.ushydrotech.com/files/6714/1409/9604/Impacts_of_Copper_on_Aquatic_Ecosystems_and_human_Health.pdf. Assessed 28 April 2020

Tamm L, Smit AB, Hospers M, Janssens SRM, Buurma S, Mølgaard JP, Lærke PE, Hansen HH, Hermans A, Bødker L, Bertrand C, Lambion J, Finckh MR, Schüler C, Lammerts van Bueren E, Ruissen T, Nielsen BJ, Solberg S, Speiser B, Wolfe MS, Phillips S, Wilcoxon S, Leifert C (2004) Assessment of the socio-economic impact of late blight and state-of-the-art management in European organic potato production systems. Research Institute of Organic Agriculture FiBL, Frick, Switzerland. ISBN 3-906081-54-0. http://www.orgprints.org/2936

Vittersø G, Torjusen H, Bernhard C, Thorjussen H, Schjøll A, Kjærnes U (2019) Survey on public opinion in Europe regarding contentious inputs - a report. Deliverables from the Organic PLUS project: pathways to phase-out contentious inputs from organic agriculture in Europe, deliverable, no. 2.2, version 1.2. Coventry University, Coventry, UK, https://organic-plus.net/. Assessed 15 April 2020

Willer H, Schlatter B, Trávníček J, Kemper L, Lernoud J (eds) (2020) The world of organic agriculture. Statistics and emerging trends 2020. Research Institute of Organic Agriculture (FiBL), Frick, Switzerland and IFOAM – Organics International, Bonn, Germany

Zappala L, Siscaro G, Biondi A, Molla O, Gonzalez-Cabrera J, Urbaneja A (2012) Efficacy of sulphur on *Tuta absoluta* and its side effects on the predator *Nesidiocoris tenuis*. J Appl Entomol 136:401–409. https://doi.org/10.1111/j.1439-0418.2011.01662.x

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.