agronomy

Article

Use of Copper-Based Fungicides in Organic Agriculture in Twelve European Countries

Lucius Tamm [1,*,†], Barbara Thuerig [1,*,†], Stoilko Apostolov [2], Hugh Blogg [3], Esmeralda Borgo [4], Paola Elisa Corneo [5,6], Susanne Fittje [7], Michelangelo de Palma [8], Adam Donko [9], Catherine Experton [10], Évelyne Alcázar Marín [11], Ángela Morell Pérez [11], Ilaria Pertot [5,6], Anton Rasmussen [12], Håvard Steinshamn [13], Airi Vetemaa [14], Helga Willer [15] and Joëlle Herforth-Rahmé [1]

1 Department of Crop Sciences, Research Institute of Organic Agriculture FiBL, 5070 Frick, Switzerland; joelle.herforth@fibl.org
2 FOA Bioselena, 4300 Karlovo, Bulgaria; s.apostolov@bioselena.com
3 Soil Association, Bristol BS1 6AD, UK; hblogg@soilassociation.org
4 Bioforum, 2018 Antwerpen, Belgium; esmeralda.borgo@bioforum.be
5 FEM Fondazione Edmund Mach, 38010 San Michele all'Adige, TN, Italy; paolaelisa.corneo@unitn.it (P.E.C.); ilaria.pertot@unitn.it (I.P.)
6 Center Agriculture Food Environment, University of Trento, 38010 San Michele all'Adige, TN, Italy
7 Naturland e.V., 82166 Gräfelfing, Germany; s.fittje@naturland.de
8 FederBio, 00198 Roma, Italy; m.depalma@agriplansrl.it
9 Hungarian Research Institute of Organic Agriculture (ÖMKI), 1174 Budapest, Hungary; adam.donko@biokutatas.hu
10 ITAB, 75595 Paris, France; catherine.experton@itab.asso.fr
11 Asociación ECOVALIA, 41013 Sevilla, Spain; ecovalia.international@ecovalia.org (É.A.M.); ecovalia.projects@ecovalia.org (Á.M.P.)
12 Innovation Centre for Organic Farming, 8200 Aarhus, Denmark; anto@icoel.dk
13 Division of Food Production and Society, Grassland and Livestock, Norwegian Institute of Bioeconomy Research NIBIO, 1430 Aas, Norway; havard.steinshamn@nibio.no
14 Estonian Organic Farming Foundation, 50403 Tartu, Estonia; airi.vetemaa@gmail.com
15 Department of Extension, Training & Communication, Research Institute of Organic Agriculture FiBL, 5070 Frick, Switzerland; helga.willer@fibl.org
* Correspondence: lucius.tamm@fibl.org (L.T.); barbara.thuerig@fibl.org (B.T.)
† These authors share first authorship.

check for updates

Citation: Tamm, L.; Thuerig, B.; Apostolov, S.; Blogg, H.; Borgo, E.; Corneo, P.E.; Fittje, S.; de Palma, M.; Donko, A.; Experton, C.; et al. Use of Copper-Based Fungicides in Organic Agriculture in Twelve European Countries. *Agronomy* **2022**, *12*, 673. https://doi.org/10.3390/agronomy12030673

Academic Editor: Giuseppe Colla

Received: 2 February 2022
Accepted: 8 March 2022
Published: 10 March 2022

Abstract: The reduction of copper-based plant-protection products with the final aim of phasing out has a high priority in European policy, as well as in organic agriculture. Our survey aims at providing an overview of the current use of these products in European organic agriculture and the need for alternatives to allow policymakers to develop strategies for a complete phasing out. Due to a lack of centralized databases on pesticide use, our survey combines expert knowledge on permitted and real copper use per crop and country, with statistics on organic area. In the 12 surveyed countries (Belgium, Bulgaria, Denmark, Estonia, France, Germany, Hungary, Italy, Norway, Spain, Switzerland, and the UK), we calculated that approximately 3258 t copper metal per year is consumed by organic agriculture, equaling to 52% of the permitted annual dosage. This amount is split between olives (1263 t y^{-1}, 39%), grapevine (990 t y^{-1}, 30%), and almonds (317 t y^{-1}, 10%), followed by other crops with much smaller annual uses (<80 t y^{-1}). In 56% of the allowed cases (countries × crops), farmers use less than half of the allowed amount, and in 27%, they use less than a quarter. At the time being, completely abandoning copper fungicides would lead to high yield losses in many crops. To successfully reduce or avoid copper use, all preventive strategies have to be fully implemented, breeding programs need to be intensified, and several affordable alternative products need to be brought to the market.

Keywords: copper-based plant-protection products; fungicides; grapevine; nuts; olives; organic agriculture; potatoes; survey

1. Introduction

The use of copper fungicides to combat plant diseases has a long tradition, dating back to the late 19th century, when Alexis Millardet accidentally discovered the efficacy of neutralized copper sulfate to reduce grapevine downy mildew [1,2]. This discovery revolutionized agricultural production by providing the first effective tool to control various phytopathogens. Although many fungicidal active substances have been discovered in the meantime, copper-based plant-protection products are still widely used in organic and conventional agriculture [2], due to their many advantages and the lack of alternatives. One of the main advantages of copper is its wide spectrum of activity against bacteria, oomycetes, ascomycetes, and basidiomycetes, including diseases of worldwide importance, such as downy mildew of grape and late blight of potato, but also secondary or minor diseases in minor crops, such as vegetables or specialty fruit [3–5]. Other favorable agronomical properties of copper include high efficacy under conditions of rain, its multisite mechanism of action that minimizes the risk of development of resistant pathogen strains, the relatively low acute toxicity for terrestrial vertebrates, and the low costs [3,5–7]. Besides its use as a fungicide, copper is also authorized as a micronutrient leaf fertilizer [8] and widely used in feed additives [9]. Micronutrient fertilizers may contain copper under the form of copper salt, copper oxide, copper hydroxide, copper chelate, and copper oxychloride, either as a copper complex or as mixtures of components (i.e., copper-based fertilizer and copper fertilizer solution) [8]. An optimal supply range for copper in plant nutrition is 0.01–0.02 mg g^{-1} dry weight measured as plant content, but requirements may depend on the crop or even the cultivar [10]. Most of the copper used as a feed additive ends up in the manure, which is considered a substantial source of copper input in arable crops and fodder production, especially when pig slurry and manures from conventional farms are imported in organic farms [11], but it has no relevance in the control of soil-borne pathogens. Being an element having scarce mobility in soil, repeated foliar applications of copper-based plant-protection products lead to copper accumulation in the soils [12] and to potentially consequent negative impacts on soil fertility (negative effects reviewed by La Torre et al. [13], for example), even though studies put the negative effects in perspective (as reviewed by Karimi et al. [14], for example).

The maximum copper quantity allowed in plant protection has been successively restricted in Europe over the last decades and is currently limited by the European plant-protection legislation to a maximum of 28 kg per ha over a period of 7 years (status 2021) (regulation (EU) 2018/1981 [15]). The final objective would be to phase copper out, as it is included in the list of candidates for substitution in the EU (Part E of the Annex to Regulation 540/2011 [16]) and Switzerland (Aktionsplan Pflanzenschutzmittel, www.BLW.admin.ch, accessed on 7 March 2022). In organic farming, copper-based plant-protection products and fertilizers are explicitly allowed according to the European Commission implementing Regulation (EC) No. 2021/1165 [17]. In addition to European legislation, EU Member States (MS) can further restrict the quantity or authorize only specific uses. For example, in five out of 27 EU member states (Denmark, Sweden, Finland, the Netherlands, and Estonia), copper is not registered as a plant-protection product. Furthermore, in a range of countries, farmer organizations self-restrict copper use beyond the legal requirements (see Section 3.1). As a consequence of overlapping EU regulations and of differences in nationally authorized plant-protection products and practices at different levels, it is difficult to get a precise overview of permitted uses (i.e., in which crops against which pathogens in which maximum quantity).

There is a substantial difference between the maximum quantity of copper permitted for a specific use (crop/disease) and its real use, as already highlighted in Switzerland, France, and Germany [18–20]. For example, a survey in Switzerland found that organic farmers use, on average, between 3 and 80% of the maximal permitted amount of copper depending on the crop, indicating a high awareness among farmers of the need to reduce copper use [18]. Katsoulas et al. [21] report considerable variability in copper use between regions and/or producers in European organic farming, depending, for example, on climatic conditions, cultivars, or production systems, and they indicate that annual copper limits were not always respected.

Even though various tools and strategies to reduce copper-based plant-protection products, such as resistant varieties, cultural measures, decision-support systems, and alternative plant-protection products, are available for farmers [22], completely abandoning copper fungicides would lead to high yield losses in many crops at the current time [19]. To develop strategies and pathways for a complete phasing out of copper-based plant-protection products, policymakers need information on the current dependency on copper-based plant-protection products, the implementation of alternative strategies, and the need for copper alternatives in European organic-crop production. Our survey aimed at (i) giving an overview on the current legal status of copper uses in organic farming in different European countries, (ii) the discovery of the main copper-consuming crops, and (iii) an estimate of the total amounts of copper consumed in European organic crop protection. The survey is based on knowledge of national experts (researchers, extension specialists, and experts from farmers' associations) from 12 European countries, including Belgium, Bulgaria, Denmark, Estonia, France, Germany, Hungary, Italy, Norway, Spain, Switzerland, and the UK.

2. Materials and Methods

2.1. Countries Included in the Study

The present survey on the theoretically allowed and real use of copper-based plant-protection products in European organic agriculture includes 12 European countries, covering all European agroclimatic zones as defined by the European Plant Protection Organisation (EPPO). Zones included are the Mediterranean (Italy, Spain, and part of France), Maritime (Belgium, part of France, Germany, Switzerland, United Kingdom, Denmark, and part of Norway), North East (Estonia and part of Norway), and Central (Bulgaria and Hungary) zones [23].

2.2. Organically Managed Area

The overall organically managed area and the organically managed area per crop for each country were obtained from Statistics.FiBL.org (accessed on 7 March 2022), which gives access to the data collected annually by the Research Institute of Organic Agriculture (FiBL) and partners (also published annually by FiBL and IFOAM—Organics International in the yearbook *The World of Organic Agriculture* [24]). Data for 2017 were used for this survey. Only selected crops were listed, and unspecific categories were excluded. The sum of the area for the selected crops does, therefore, not correspond with the total organic farmland for a country.

2.3. Permitted and Real Copper Use

The European pesticide database was consulted for approval of copper compounds as active substances in the involved countries [25] and amended by information on emergency approvals at the national level. National databases (e.g., listed by the European and Mediterranean Plant Protection Organisation EPPO [26]) were checked for permission of copper-based plant-protection products and permitted uses (crops, dosages in kg ha^{-1}). This information was further verified and supplemented by national experts from research institutes, farmers' associations or extension services participating in the EU project on which this survey is based, or by experts in their network, amounting to 29 involved national experts (Table 1). This expertise was included to fill knowledge gaps, as plant-protection products are also allowed for use by way of emergency registrations (SANCO/10087/2013, ref. [27]), minor use registrations [28], or special national instruments, such as Off-Label Extension of Authorisation for Minor uses (EAMU) (http://www.eumuda.eu/) (accessed on 7 March 2022), and this is not mapped in the EU pesticide database.

Table 1. Institutes involved in this expert survey.

Country	Organization Involved	Website *
Belgium	Bioforum	https://www.bioforum.be
Bulgaria	Bioselena	https://bioselena.com
Denmark	Økologisk Landsforening	https://okologi.dk
Estonia	Estonian Organic Farming Foundation (EOFF)	http://www.maheklubi.ee
France	Institut de l'Agriculture et de l'Alimentation Biologiques (ITAB)	http://itab.asso.fr
Germany	Naturland	https://naturland.de
Hungary	Hungarian Research Institute of Organic Agriculture (ÖMKi)	https://www.biokutatas.hu
Italy	FederBio,	https://feder.bio
	Fondazione Edmund Mach (FEM)	https://www.fmach.it
Norway	Norwegian Institute of Bioeconomy Research (NIBIO)	https://www.nibio.no
Spain	Ecovalia	https://www.ecovalia.org
Switzerland	Research Institute of Organic Agriculture (FiBL)	https://www.fibl.org
United Kingdom	Soil Association	https://www.soilassociation.org

* all websites last accessed 7 March 2022.

For each crop where the use is permitted, real average copper use by organic farmers (in kg ha^{-1}) was estimated by the national experts for each country. A total of 115 crops or crop categories (according to Statistics.FiBL.org) (accessed on 7 March 2022) were evaluated. Out of these 115 crops/crop categories, 51 were perennial crops/crop categories and 64 were annual crops/crop categories.

2.4. Alternative Crop-Protection Strategies

For key crops, a description of the most widely used crop-protection strategies, targeted on diseases controlled by copper, was compiled based on the knowhow of national experts of relevant countries. Moreover, the immediate potential for further reduction of copper use—which does not compromise yield stability—was assessed (summarized in Supplementary Materials Table S1).

2.5. Calculations and Statistics

The amount of copper allowed in organic plant protection was calculated for each crop and country as follows:

$$\text{Copper}_{\text{allowed}}\ (\text{kg y}^{-1}) = \text{Area (ha)} \times \text{permitted use (kg ha}^{-1}\ \text{y}^{-1})$$

The amount of copper really used in organic plant protection was calculated for each crop and country as follows:

$$\text{Copper}_{\text{used}}\ (\text{kg y}^{-1}) = \text{Area (ha)} \times \text{estimated real use (kg ha}^{-1}\ \text{y}^{-1})$$

The amount of copper really used by organic farmers was put into perspective with the allowed amount for each crop and country as follows:

$$\text{Copper utilization rate} = (\text{Copper}_{\text{used}}) \times (\text{Copper}_{\text{allowed}})^{-1}$$

The Pearson correlation coefficient was calculated by using the software IBM SPSS Statistics for Windows (IBM Corp. Released 2015. Version 23.0. Armonk, NY, USA: IBM Corp.).

3. Results

3.1. Authorized Uses of Copper in European Agriculture

While copper compounds are approved as active substances for plant protection at EU level (Regulation (EC) No. 1107/2009 [29]), plant-protection products containing copper are registered for the use in individual crops and against individual pathogens at the national level, resulting in different copper limits for individual cases (countries × crop).

Our survey shows that copper-based plant-protection products are registered in 25 out of 30 European countries (22 EU member states, as well as the non-EU countries, namely Norway, Switzerland, and the United Kingdom). In five out of 27 EU member states, copper is not registered as an active substance (Denmark, Sweden, Finland, the Netherlands, and Estonia). The copper compounds authorized as active substances in fungicides in the EU are Bordeaux mixture, copper hydroxide, copper oxide, copper oxychloride, and tribasic copper sulfate. However, not every copper compound is registered in each country. Copper hydroxide and oxychloride are both registered in 22 countries, followed by tribasic copper sulfate (16 countries), copper oxide (12 countries), and Bordeaux mixture (ten countries) (Supplementary Materials Table S2).

Different overlapping European and national regulations, the lack of centralized databases, and additional self-restrictions beyond the legal requirements by national label organizations make it difficult to get an overview on allowed copper uses (country/crops/pathogens) and the limits that apply. At the international level, Demeter International limits the amount averaged over 7 years to 3 kg ha^{-1} y^{-1} and recommends a maximum of 500 g/ha/spray [30]. The Demeter International standard allows for exemptions in wine- and hop-growing regions with high fungal pressure. In these cases, the respective certifying organization may grant an exemption for the use of an average amount of up to 4 kg ha^{-1} y^{-1} over 5 years for grapes and hops. At the national level, associations such as Bio Austria (AT), Bioland (DE), Naturland (DE), Bio Suisse (CH), or PRO-BIO (CZ) defined crop-specific limitations. Copper limits set by private standards are summarized in Table 2; case-specific (i.e., country × crop) limits are summarized in Figures 1 and 2 and are discussed in the next section.

The use of micronutrients fertilizers with copper was not found to be specifically limited in any country. However, some private organic standards restrict their use (Table 2). For example, Bio Suisse (CH) (https://partner.bio-suisse.ch/de/regelwerkemerkbltter.php) (accessed on 7 March 2022) and KRAV (SE) (https://www.krav.se/en/standards/) (accessed on 7 March 2022) follow the policy not to allow micronutrient fertilizers containing copper without proof of necessity. In contrast, we found that micronutrient leaf fertilizers are allowed and used in organic farming in Denmark and the Netherlands, where the use of copper-based plant-protection products is not allowed.

In fertilizers containing the macronutrients ammonium (N), phosphorous (P), potassium (K), magnesium (Mg), and calcium (Ca), copper is considered a contaminant, and maximum levels are defined. Here, the copper content in an organic fertilizer must not exceed 300 mg kg^{-1} dry matter by Regulation (EU) 2019/1009 [31]. However, we found that fertilizers do not undergo stringent approval procedures in many European countries, and the full composition is rarely divulged by the manufacturer. Furthermore, leaf fertilizers may contain substances with well-known plant-protection properties, such as copper; phosphonate; or even insecticides, such as Matrine [32]. Harmonization is intended on the European level for the future, as the new Fertilizer Regulation offers optional harmonization: In order to get the CE marking, the requirements of the new regulation have to be met. For their internal markets, the EU member states will still have the possibility to set specific rules, and it is still possible to recognize products mutually (Regulation (EU) 2019/1009, ref. [31]).

Beyond European regulation, an increasing number of organic farmers' associations and certifiers have joined forces to develop a harmonized and transparent inputs assessment scheme to facilitate use of high-quality products in organic farming (https://www.inputs.eu/ [33]) (accessed on 7 March 2022). At present, the network publishes input lists for Austria (AT), Croatia (HR), Germany (DE), Italy (IT), Netherlands (NL), Sweden (SE), and Switzerland (CH).

Table 2. Restrictions of copper use in the private sector by farmers' associations in 19 selected European countries.

Country	National Level	National/Private Standards				Restrictions on Copper Fertilizers
		Demeter	Other Standards			
			Standard	Max Copper ha^{-1} year^{-1} as PPP	Other Restrictions	
AT		Demeter International [$]	BIO AUSTRIA	Arable crops 2 kg, fruits 3 kg, wine 3 kg, hops 4 kg. More only after approval by Bio AUSTRIA		
BE		Demeter International	EU			
CH		Cu only in fruit and vine, without under cultivation of feed plants. Viticulture 3 kg on average over 5 y (max 4 kg y^{-1}), pome fruit 1.5 kg. If Bio Suisse increases amount of Cu due to serious incidents, this value (max 4 kg) is adopted for individual years.	Bio Suisse	4 kg, apple and pears 1.5 kg, berries 2 kg. Arable crops must not be treated with copper, except for potatoes, vegetables and hops		Not allowed without proof of necessity
			FOAG [$$]	4 kg or not more than 20 kg averaged over 5 consecutive years		
CZ		Demeter International	PRO-BIO 2004	3 kg	Copper soil content to be analyzed each 6th year if copper preparations are used	
DE		Demeter International	Bioland	3 kg, hops 4 kg, potato only with special authorization from Bioland	Copper content of soil to be continuously determined if copper preparations are used	
			Naturland	3 kg (including potatoes), hops 4 kg		
DK	No Cu PPP registered *	-	-			
EE	No Cu PPP registered	-	-			
ES		Demeter International	EU, with annual limitation of 4 kg			
FI	No Cu PPP registered	-	-			
FR		Demeter International	EU			

Table 2. *Cont.*

Country	National Level	National/Private Standards				Restrictions on Copper Fertilizers
		Demeter	Other Standards			
			Standard	Max Copper ha^{-1} $year^{-1}$ as PPP	Other Restrictions	
HU		Demeter International	EU			
IT		Demeter International	EU			
NL			SKAL	Not allowed		Allowed
NO		Demeter International				Not allowed without proof of necessity.
PL		Demeter International	EU			
RO		Demeter International	EU			
SE	No Cu PPP registered		KRAV	Not allowed (amounts of copper required exceed KRAV's limit for addition of heavy metals)	Maximum limits for heavy metals (Pb, Cd, Cu, Cr, Hg, Ni, Zn) including inputs by fertilizers, soil conditioners, PPP, herbicides or indirect inputs by use in animal husbandry (feed, feed minerals and medicines). Fertilizers/soil conditioners to be analyzed when high concentrations of contaminants are expected	300 g ha^{-1} y^{-1}; Up to max 1 kg permitted if shown that arable land in question requires additional copper
SI					Annual production plan required as basis for use of any plant-protection substances from the list of allowed PPP (Annex), agreement from inspection body needed.	

$ Demeter International: max 3 kg averaged over 7 years, preferably max 500 g ha−1 spray−1; * thus use in plant protection not allowed; $$ Federal Office of Agriculture. AT, Austria; BE, Belgium; CH, Switzerland; CZ, Czechia; DE, Germany; DK, Denmark; EE, Estonia; ES, Spain; FI, Finland; FR, France; HU, Hungary; IT, Italy; NL, Netherlands; NO, Norway; PL, Poland; RO, Romania; SE, Sweden; SI, Slovenia.

EPPO code[a]	Crop	Belgium	Bulgaria	France	Germany	Hungary	Italy	Norway	Spain	Switzerland	UK
PRNDU	Almonds			4 / 1.5			4 / 4		4 / 2		
MABSD	Apples	2.6 / 2.6	4 / 4	4 / 3	3 / 1.3	3 / 3	4 / 1.5	3 / 3	4 / 1.5	4 / 0.9	4 / 2
PRNAR	Apricots		2 / 1.5	4 / 2.5		3 / 3	4 / 4			4 / 2	
PEBAM	Avocados						4 / 0				
MUBPA	Bananas										
	Berries, no details/n.e.c.		4 / 2.5		3 / 0.7		4 / 0			4 / 2	
	Berries, other				0.7						
	Black chokeberries										
RUBFR	Blackberries				3 / 0.7		4 / 3			4 / 2	
VACMY	Blueberries				3 / 0.7		4 / 3			4 / 2	
RHACT	Buckthorn										
PRfalschV	Cherries	2.6 / 2.6	4 / 3.5	4 / 2.5	4 / 3		4 / 4			4 / 2	4 / 0
CONSVA	Chestnuts			4 / 0							
	Citrus no detail			4 / 2			4 / 2		4 / 2.5		
RIBNI	Currants			4 / 0.3			4 / 3				
PHXDA	Dates										
FIUCA	Figs						4 / 0				
	Fruit, temperate, no details										
	Fruit, temperate, other										
	Fruit, tropical and subtropical, no details										
	Fruit, tropical and subtropical, other										
CIDPA	Grapefruit/Pomelos			4 / 2.5							
1VITG	Grapes, no details	2.6 / 2.6	4 / 4	4 / 4	3 / 2.3	3 / 3	4 / 4			4 / 2.9	4 / 0
	Grapes, raisins			4 / 4						/	
	Grapes, table			4 / 4			4 / 4		4 / 2	4 / 2.9	
1VITG	Grapes, wine	2.6 / 2.6	4 / 4	4 / 4	3 / 2.3	3 / 3	4 / 4		4 / 2	4 / 2.9	4 / 0
CYLAV	Hazelnuts			4 / 4			4 / 4		1.2 / 1		
HOPSS	Hops	2 / 2		4 / 4	4 / 3.7					4 / 4	
ATICH	Kiwis			4 / 3.3			4 / 4				
CIDLI	Lemons and limes			4 / 2			4 / 3				
PRNPN	Nectarines		4 / 2	4 / 2.5			4 / 4		4 / 1.5		
	Nuts, no details		4 / 1.7	4 / 4		4 / 3					
	Nuts, other										
OLVEU	Olives, no details			4 / 2			4 3		4 2.8		
	Olives, oil			4 / 2			4 / 3		4 / 2.8		
CIDSI	Oranges			4 / 2			4 / 2		4 / 2.5		
PRNPS	Peaches		4 / 2.5	4 / 2.5	3 / 0	4 / 3	4 / 4				
	Peaches and nectarines, no details										
PYUCO	Pears	2.6 / 2.6	4 / 2.5	4 / 3	3 / 1.3	4 / 3.5	4 / 4	3.5 / 2.5		4 / 1.2	4 / 2
PIAVE	Pistachios										
3PLUC	Plums	2.6 / 2.6	4 / 1.8	4 / 2	4 / 2.5		4 / 4	3 / 0		4 / 1.5	4 / 0
	Pome fruit, no details										
	Pome fruit, other										
PUNGR	Pomegranate										
CYDOB	Quinces										
RUBID	Raspberries			4 / 0.6	3 / 0.5		4 / 3			4 / 0.5	
	Stone fruit, no details				/ 1					4 / 4	3 / 0
	Stone fruit, other		4 / 1.5		3 / 1				4 / na	4 / 4	3 / 0
FRAAN	Strawberries		4 / 1.2	4 / 2	3 / 0.8		4 / 4		4 / 0	2 / 0.4	3 / 0
CIDRE	Tangerine										
NNNTE	Tea										
IUGRE	Walnuts, with shell			4 / na	3 / 0		4 / 4		2 / na	4 / 0	

Figure 1. Copper-use authorizations and estimated real use in perennial crops in organic farming (authorized use/real use) in kg per ha and year in organic farming in the 12 surveyed European countries. Colors visualize intensity of use (from no use (white) to a maximum of 4 kg (dark blue)). [a] EPPO codes according EPPO Global Database. https://gd.eppo.int (accessed on 7 March 2022).

EPPO code[a]	Crop	Belgium	Bulgaria	Fracne	Germany	Hungary	Italy	Norway	Spain	Switzerland	UK
HHHHHH	Aromatic, medical and culinary plants										
1ASPG	Asparagus										
SOLME	Aubergine						4 / 4			1.33 / 1.3	
3BARC	Barley		4 / 0.5			4 / 0	4 / 0.5		4 / 0.5		
VICFX	Beans			4 / 2					4 / 4		
3BRAC	Brassicas						4 / 3		2 / na	4 / 2	
FAGES	Buckwheat										
DAUCS	Carrots			4 / 2					2 / na	4 / 2.8	
APUGR & AI	Celeriac and celery									4 / 2.7	
CICIN	Chicory / red chicory	2 / 2		4 / 2							
CMJSP	Cotton										
LIUUT	Flax										
BEAVC	Fodder beet									4 / 0	
ZEAMX	Grain maize and corn cob mix										
CNISA	Hemp										
	Industrial crops, no details										
	Industrial crops, other										
ALLPO	Leeks										
LENCU	Lentils										
LACSA	Lettuce								4 / na		
LIUUT	Linseed (oil flax)						4 / 0				
3LUPC	Lupine										
OATSS	Oats						4 / 0				
	Oilseeds, no details										
	Oilseeds, other, n.e.c						4 / 0				
ALLCE	Onions			4 / 2							
	Other cereals n.e.c.						4 / 0				
	Other fodder roots										
PEAAC	Peas			4 / 2	3 / 0						
1CPSG	Pepper/Capsicum										
SOLTU	Potatoes	4 / 4	4 / 0.5	4 / 4	3 / 1.6		4 / 3		4 / na	4 / 2.8	4 / 3.7
	Protein crops, no details						4 / 0.5				
	Protein crops, other										
	Pulses					4 / 2					
CUUPE	Pumpkin seeds									4 / 0	
3TURC	Rape and turnip rape						4 / 2				
ORYSA	Rice						4 / 0				
	Root crops, no details										
	Root crops, other, n.e.c			4 / 2			4 / 2			4 / 1	3 / 0
3RYEC	Rye						4 / 1				3 / 0
GLXMA	Soybeans						4 / 0				
	Spelt										
SPQOL	Spinach										
BEAVP	Sugar beet						4 / 1		2 / na	4 / 0	3 / 0
1SACG	Sugarcane						4 / 4				
HELAN	Sunflower seed						4 / 0				
	Textile crops, no details										
	Textile crops, other, n.e.c.										
NIOTA	Tobacco										
LYPXS/LYPX	Tomatoes			4 / 4			4 / 4		4 / 4	4 / 0.2	
3TRIC	Triticale										
	Vegetables, fruit		4 / 0.2				4 / 4		4 / 4		
	Vegetables, leafy or stalked			4 / 2							
	Vegetables, Broccoli			4 / 2							
	Vegetables, no details			4 / 2							
	Vegetables, other			4 / 2							
	Vegetables, root tuber and bulb			4 / 2					4 / 0		
3WHEC	Wheat						4 / 0.1				
	Greenhouse tomato	2 / 1		4 / 2	3 / 1.4		4 / 4		4 / 2	4 / 0.2	2 / 0
	Greenhouse cucumber			4 / 2					4 /	4 / 0.2	2 / 0
	Greenhouse other			4 / 2	3 / 1.4				4 / 2		
	Greenhouse ornamentals	2 / 1		4 / 2	3 / 1.5				4 / 2	4 / 0	2 / 0
	Outdoors ornamentals		4 / 2.9	4 / 2					4 / 2		

Figure 2. Copper-use authorizations and estimated real use (authorized use/ real use) in annual crops in kg per ha and year in organic farming in the 12 surveyed European countries. Colors visualize intensity of use (from no use (white) to a maximum of 4 kg (dark blue)). [a] EPPO codes according EPPO Global Database. https://gd.eppo.int (accessed on 7 March 2022).

3.2. Copper Use by European Organic Farmers

3.2.1. Copper Use Authorization and Estimated Real Use Per Hectare and Year

This survey in the 12 selected European countries covers 2.9 million hectares of organically managed horticultural (temperate fruits; grapes; olives; nuts; and vegetables, including potato) and arable crops. Permanent grasslands were not included. The use of copper is permitted on a total 1.55 million hectares. Among the countries included in the survey, Italy, Spain, and France represent the largest areas of horticultural crops in organic production in Europe (75%). Together with the other nine countries included in this survey, 83% of the organically managed European (EU + Switzerland + UK + Norway) horticultural area is covered (Supplementary Materials Table S3).

Copper as a plant-protection product is permitted on a wide range of perennial (Figure 1), as well as on selected vegetable, crops (Figure 2) in the 12 surveyed European countries. In arable crops (Figure 2), copper is only used on potato as a plant-protection product, but it is sometimes used as a leaf fertilizer, without expectations regarding disease control. The number of uses allowed per country depends directly on whether the climate is suitable for certain crops. In Italy, Spain, and France, copper is allowed in more than 40 crops/crop categories (Figures 1 and 2). In the Southern Central European countries, such as Germany or Switzerland, the use is permitted on approximately 20 crops, whereas in the Northern Central European countries, five to ten uses are registered. In the examined countries, copper is mainly allowed on apple and grapevine (12 countries), pear (eleven), potatoes and plums (eight each), and cherries and strawberries (seven each) (Figures 1 and 2). Some crops, such as olives or almonds, are only grown in a few of the surveyed countries; thus, consequently, only a few allowed uses are registered. Permitted amounts of copper vary between 1.2 and 4 kg ha^{-1}, but they are between 3 and 4 kg ha^{-1} y^{-1} in most cases (crops × country). In Italy and France, in all permitted cases, 4 kg ha^{-1} is allowed. In other countries (e.g., Switzerland, Germany, and Spain), permitted amounts vary depending on the crop.

Organic farmers use between 0 and 100% of the maximum allowed amount of copper depending on the crop and/or country, i.e., copper utilization rates ($copper_{used}$) × ($copper_{allowed}$)$^{-1}$) ranged between 0 and 1. Over all surveyed countries, copper-utilization rates were <0.25 in 27% of the allowed cases (crops × country), <0.5 in 56%, and >0.75 in 27% of the allowed cases (Table 3), with some variability between countries. The UK showed the highest percentage of cases with utilization rates < 0.5 (94%), followed by Germany (70% of cases), Switzerland (67%), Spain (62%), France (61%), Bulgaria (47%), and Italy (41%). The relatively high percentage of cases with high copper-utilization rates in Belgium, Norway, and Hungary has to be put into perspective with low maximum permitted copper quantities (2–2.6 kg ha^{-1} y^{-1} in Belgium for all crops except potatoes; 3 kg ha^{-1} y^{-1} in Norway and Hungary) in most crops and, for Norway, with a very limited number of permitted uses (3 crops). Copper utilization rates vary between crops (Figures 1 and 2). For example, in apples, 3–4 kg ha^{-1} y^{-1} is permitted in Germany, Spain, Switzerland, or the UK, but, on average, only 1–2 kg is used. In other crops, limits are often fully exploited, even though differences between countries may exist. For example, in grapevine, the maximum allowed amount of copper is used in five out of the eight countries which allow its use.

Table 3. Overview on copper-utilization rates in organic farming in 12 selected European countries.

Utilization Rates [a]	Belgium		Bulgaria		France		Germany		Hungary		Italy		Norway		Spain		Switzerland		UK		Overall (%) [d]
	No. [b]	% [c]	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
0–0.25	0	0.0	3	17.6	3	6.8	7	35.0	1	11.1	15	31.3	1	33.3	4	19.0	12	40.0	13	81.3	27
0.26–0.5	2	18.2	5	29.4	24	54.5	7	35.0	1	11.1	5	10.4	0	0.0	9	42.9	8	26.7	2	12.5	29
0.51–0.75	0	0.0	5	29.4	7	15.9	3	15.0	2	22.2	9	18.8	1	33.3	4	19.0	6	20.0	0	0.0	17
0.76–1	9	81.8	4	23.5	10	22.7	3	15.0	5	55.6	19	39.6	1	33.3	4	19.0	4	13.3	1	6.3	27
Total permitted uses	11		17		44		20		9		48		3		21		30		16		

[a] Utilization rates: (estimated real copper use)/(permitted use per crop). [b] Number of crops per utilization rate category. [c] Percentage of crops per utilization rate category. [d] Overall (%): (number of cases per utilization rate category)/(total number of allowed cases).

3.2.2. Annual Copper Use

In order to put copper use in organic farming into perspective with its impact on the economy and the environment, copper consumption was calculated for each case (crop × country) by multiplying the amount of copper allowed/used (kg ha^{-1}) by the corresponding cultivated area (ha). Overall, organic farmers in the 12 surveyed countries made use of about 53% of the total authorized amount of copper, equaling to approximately 3 300 t of copper metal per year (Table 4).

Table 4. Maximum permitted amounts of copper (t y^{-1}), total estimated real use (t y^{-1}), and percentage utilization in organic farming in the 12 surveyed European countries.

	Belgium	**Bulgaria**	**Denmark**	**Estonia**	**France**	**Germany**	**Hungary**	**Italy**	**Norway**	**Spain**	**Switzerland**	**United Kingdom**	**Total of 12 Countries**
Maximum permitted quantities (t)	3.9	248	0	0	546	91	34.4	3253	0.6	2038	10.4	11.5	6236
Total estimated real use (t)	3.9	67	0	0	473	42	22.1	1556	0.5	1081	7.1	6.2	3259
Percentage utilisation [a]	100%	27%			87%	46%	64%	48%	78%	53%	68%	54%	52%

[a] Percentage utilization: (total estimated real use (t))/(maximum permitted quantities (t)).

Among the countries included in this survey, the highest amounts of copper per year were used in Italy (approximately 1 550 t), Spain (approximately 1 100 t), and France (approximately 500 t), followed by Bulgaria (67 t), Germany (42 t), and Hungary (22 t). Copper use was highly correlated to the organically managed area on which copper use is allowed ($R^2 = 0.941$, $p < 0.01$, Pearson), which obviously depends on the size of the country, the share of organically managed land, the cultivated crops, and the copper authorizations in these crops.

In the 12 surveyed countries, olive production with an estimated 1263 t, grapevine production with 990 t, and almonds with 317 t account together for nearly 80% of the estimated annual copper use (Figure 3). Nuts (no details), apples, vegetables (fruit), oranges, hazelnuts, vegetables (no details), potatoes, and barley (as fertilizer) each use between 40 and 80 t per year, accounting together for 14% of total copper consumption. Protein crops, lemons and lime, cherries, citrus (no detail), kiwis, brassicas, wheat (as fertilizer), apricots, plums, pears, and peaches each use between 10 and 25 t per year, accounting together for 6% of total annual copper use. All other crops/categories use less than 10 t per year. After aggregating crops into crop categories (Figure 4), "vegetable crops" (aggregating "vegetables fruit" and "vegetables no details") rank fourth (106 t y^{-1}, 3.3%) after the top three categories, namely "olives" (1 263 t y^{-1}, 38.8%), "grapes" (990 t y^{-1}, 30.4%), and "nuts" (aggregating "almonds", "hazelnuts", "nuts no details", and "walnuts") (459 t y^{-1}, 14%). "Citrus fruit" ranks fifth (102 t y^{-1}, 3.1%), before "pome fruit" (78 t y^{-1}, 2.4%), "cereals" (72 t y^{-1}, 2.2%, fertilizer use), and "stone fruit" (67 t y^{-1}, 2.1%) in the 12 surveyed countries (Figure 4). Potatoes only ranked ninth, with 39 t y^{-1} (1.2%).

Crops	Belgium	Bulgaria	France	Germany	Hungary	Italy	Norway	Spain	Switzer-land	UK	Total per crop
Almonds	0	0	0	0	0	70	0	248	0	0	318
Apples	0.6	2.4	31	7.9	8.1	9.3	0.5	1.8	0.3	1.8	64
Apricots	0	0	2.6	0	0.6	12	0	0	0	0	16
Barley	0	0.6	0	0	0	20	0	33	0	0	54
Berries, nd	0	4.2	0	0	0	0	0	0	0.4	0	5
Blueberries	0	0	0	0	0	0	0	0	0	0	0
Brassicas	0	0	0	0	0	19	0	0	0	0	19
Cherries	0.03	6.2	1.1	0	0	16	0	0	0	0	23
Citrus, nd	0	0	0.8	0	0	21	0	0	0	0	22
Currants	0	0	0	0	0	0	0	0	0	0	0
Grapes	0.1	16	314	17	5.1	422	0	214	2.9	0	991
Hazelnuts	0	0	0	0	0	49	0	0	0	0	49
Hops	0.03	0	0	0.7	0	0	0	0	0	0	1
Kiwis	0	0	0	0	0	22	0	0	0	0	22
Lemons and limes	0	0	0	0	0	24	0	0	0	0	24
Nectarines	0	0	0.5	0	0	1.3	0	0.8	0	0	3
Nuts, nd	0	31	49	0	6.1	0	0	0	0	0	86
Olives, oil	0	0	9.5	0	0	707	0	546	0	0	1263
Oranges	0	0	0	0	0	42	0	14	0	0	56
Peaches	0	0.6	1.1	0	0.2	8.9	0	0	0	0	11
Pears	0.2	0	3.6	0.5	0.7	8.1	0.02	0	0.1	0.2	14
Plums	0	4.8	4.1	0	0	4.9	0	0	0	0	14
Potatoes	2.9	0	12	14	0	3.9	0	0	2.3	4.2	39
Protein crops, nd	0	0	0	0	0	25	0	0	0	0	25
Pulses	0	0	0	0	1.1	0	0	0	0	0	1
Rape and turnip rape	0	0	0	0	0	4.1	0	0	0	0	4
Raspberries	0	0	0	0	0	0	0	0	0	0	0
Root crops, other	0	0	1.3	0	0	0.8	0	0	0	0	2
Rye	0	0	0	0	0	0	0	0	0	0	0
Stone fruit, nd	0	0	0	1.1	0	0	0	0	0.4	0	1
Strawberries	0	0	0	0	0	1.0	0	0	0	0	2
Sugar beet	0	0	0	0	0	0	0	0	0	0	0
Vegetables, fruit	0	0	0	0	0	41	0	23	0	0	63
Vegetables, nd	0	0	42	0	0	0	0	0	0.6	0	42
Walnuts, with shell	0	0	0	0	0	5.9	0	0	0	0	6
Wheat	0	0	0	0	0	18	0	0	0	0	18
Total per country	**3.9**	**67**	**464**	**42**	**22**	**1556**	**0.5**	**1081**	**7.1**	**6.2**	**3259**

Figure 3. Total estimated copper consumption (t y^{-1}) in organic farming in the 12 surveyed European countries in different horticultural crops (temperate fruits; grapes; olives; nuts; and vegetables, including potatoes). Gray bars visualize the relative contribution of a crop to overall copper consumption in an individual country.

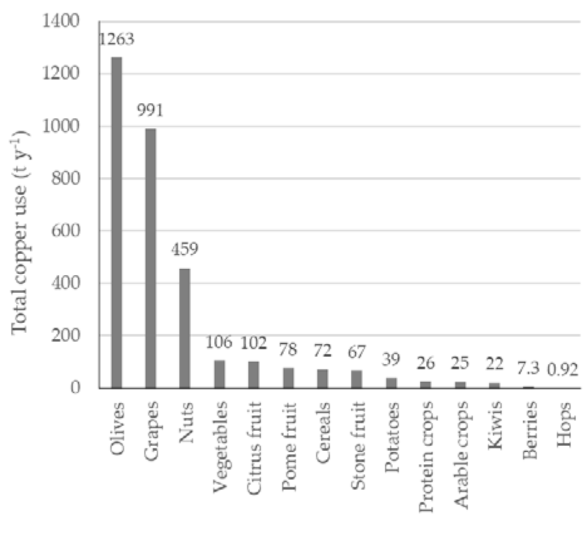

Figure 4. Total estimated copper consumption (t y^{-1}) in organic farming in the 12 surveyed European countries. Crops were aggregated into crop categories (for details, see Supplementary Materials).

The ranking of relative importance differs substantially between countries. In Belgium, where application is allowed in seven crops, potatoes accounts for 78% of copper consumption, followed by apples (13%) and pears (5%) (Figure 3). In Bulgaria, where 14 uses are permitted, nuts and grapevine use 69% of the total quantity, followed by cherries (9%). In France, grapevine is where the most important use is made (68%), followed by nuts (11%), vegetables (9%), apples (7%), and potatoes (2.5%), with much smaller quantities. In Germany, copper use is relatively equally distributed between grapevine (40%), potatoes (34%), and apples (19%). In Hungary, copper is preferably used on apples (37%), nuts (28%), and grapes (23%). In Italy, an extraordinary wide range of uses is permitted. Olives (45%) and grapevine (27%) alone use up 72% of the total copper, followed by nuts and almonds (8%), citrus fruits (aggregating "lemons and limes", "oranges", and "citrus no details") (5.6%), and vegetables (2.6%). Quite remarkably, the amount of copper used on barley and wheat (together 2.5%) as a fertilizer appears much higher than the amount used as a plant-protection product on many important crops, such as apples, cherries, apricots, peaches, pears, and plums (all < 1%). The amount of copper used in Norway with 0.5 t y^{-1} is minimal in comparison to other countries and concentrates on apples (97%) and pears (3%). In Spain, the largest amounts of copper are used in olives (51%), almonds (23%), and grapes (20%), together accounting for 94% of the copper used. As in Italy, the use as a fertilizer in barley with 3% is higher than in plant protection on other crops, such as vegetables, oranges, apples, and nectarines (together below 2%). In Switzerland, copper use concentrates on grapevine (41%) and potatoes (32%), followed by vegetables (9%), stone fruits (6%), berries (5%), apples (4.7%), and pears (1.3%) at much lower quantities. In the UK, potatoes are the most important use (69%), followed by apples (28%) and pears (3%).

4. Discussion

Even though organic agriculture strictly regulates the use of inputs, organic farmers in Europe still use some inputs generally thought to be contentious (anthelmintics, antibiotics, and vitamins in livestock management; and external nutrient inputs, mineral oil pesticides, and copper-based fungicides in plant production) [34]. However, the reduction or substitution of these inputs has high priority in European agricultural policy and for organic-farming associations. This study on the current use of copper-based fungicides was performed within the EU-funded project RELACS, in which surveys and studies related to all of the contentious inputs listed above were conducted. While this publication gives an in-depth analysis and discussion on the use of copper-based fungicides, the main findings of this survey and the surveys on the other contentious inputs investigated within RELACS have been summarized by Varga et al. [34], putting them into a larger perspective.

For copper-based fungicides, there is a lack of data on their use, in particular, with regard to total consumption, leading to ambiguities regarding the quantities to be replaced. The present study aimed at filling this data gap by combining an expert survey on use of copper in individual crops with land-use data in 12 European countries, and therefore covering 84% of the European horticultural area. Other studies assessing copper use in organic agriculture have either focused on certain regions (e.g., Switzerland [18] or Germany [19]) or on specific crops (e.g., olives, citrus, tomatoes, and potatoes [21]). The present survey takes into account reductions of copper limits (from 6 kg ha^{-1} y^{-1} to 28 kg ha^{-1} in 7 years) after 2018 as a result of regulation (EU)2018/1981 [15], while other surveys which were conducted before 2018 [18,19,21] use the limits in force at that time, which has to be taken into account when comparing results.

4.1. Copper Use Authorization and Estimated Real Use Per Hectare and Year

The extraordinary wide spectrum of copper is reflected in the presence of more than 60 permitted and more than 40 real uses identified in this survey. The wide range of activity emphasizes the particular challenge for substitution of copper-based fungicides, requiring a broad range of solutions tailored to each crop and plant pathogen. The number of allowed and real uses strongly varies between countries mainly as a result of the size of a country and the proportion of the organically managed area. Furthermore, it also relates to the climatic conditions, i.e., whether weather conditions are favorable to grow certain crops or to occurrence and severity of certain plant diseases. Therefore, countries such as Spain, Italy, and France, by far, have the highest number of permitted and real uses.

Permitted amounts of copper ranged from 1.2 to 4 kg ha^{-1}, with a focus on 3 to 4 kg ha^{-1}. In more than 50% of these cases (crop × country), experts assessed that farmers use, on average, less than half of the permitted copper quantities. These results are consistent with results from other surveys [18,21]. For example, in a Swiss survey among organic farmers performed in 2009–2012, utilization rates below 50% were found in nine out of 15 allowed uses [18]. Low utilization rates in many crops reflects the high awareness of individual farmers to reduce the amount of copper, as well as the efforts of farmers' associations and national copper-reduction strategies. High utilization rates in particular crops in most surveyed countries can be indicative for crop protection issues which are difficult to solve without copper use, such as for grapevine and downy mildew (*Plasmopara viticola*) [2]. In other cases, high utilization rates mirror restrictive copper limits as, for example, for Belgium, where the permitted amount of copper is set to 2–2.6 kg ha^{-1} (exceptions: potatoes, 4 kg ha^{-1}), resulting in utilization rates above 75% in most of the cases. In some crops, a high variability in the copper utilization rate between countries was observed. For example, in potatoes, on average, between 10 and 100% of the maximal legally permitted amount is used depending on the country. This might reflect different climatic conditions and, thus, disease pressure: *Phytophthora infestans*, causing late blight in potato, prefers humid, cool conditions, and, consequently, utilization rates are high in Belgium, Germany, Switzerland, and the UK. For potatoes and tomatoes in Italy, the copper-use estimates in this survey are consistent with those of Katsoulas, et al. [21], considering that, in Italy, limits have been reduced to 4 kg ha^{-1} y^{-1} in the meanwhile. In some other cases, the two studies' estimates of real copper use differ from each other, often with higher estimates in Katsoulas et al. [21]. This discrepancy might reflect increased reduction efforts as a result of the reduced legally permitted maximum copper quantity after 2018 ((EU) 2018/1981 [15]). Furthermore, variability of copper uses depending on varieties or production systems could lead to different assessments by experts. For example, in olives, Katsoulas et al. [21] found higher amounts of copper used in irrigated vs. non-irrigated systems, and in susceptible vs. less susceptible varieties, and Speiser et al. [18] report much lower copper utilization rates in downy mildew resistant ("PiWi") than in susceptible cultivars (13% vs. 75%).

4.2. Annual Copper Use

In view of the intended copper replacement in the coming years, an estimate of the quantities of plant-protection products needed for replacement is crucial. This survey estimates that more than 3200 t of copper needs to be substituted annually in the 12 surveyed countries to cover the needs of the current organic production area. Thus, with an average amount of 0.5 kg copper per ha and treatment, alternative products sufficient to treat 64,000 km^2 once a year would be necessary for the 12 surveyed countries. This calculation does not consider the foreseen increase in organically managed area or the potential increase of diseases due to climate change or the introduction of new plant pathogens. Due to the substantial lack of statistics on active substance use [35], the verification of copper-use data is not straightforward. At least for Germany and Switzerland, plausibility checks can be performed. In Switzerland, the sales of copper as a plant-protection product are 50 t y^{-1} [36]. This survey's estimate of 7 t y^{-1} used for plant protection in Swiss organic farming thus corresponds to approximately 14% of total copper use, which, in turn, is proportional to the organic farming area (i.e., 14% organic area share of total farmland in 2017, https://statistics.fibl.org/europe/area.html) (accessed on 7 March 2022), and thus plausible. For Germany, Kühne et al. [19] estimated a total use of copper of 26 t in organic farming in 2013. The 42 t y^{-1} calculated in this study (corresponding to an increase of 61%) is in accordance with these findings, given the growth of the organic sector (+75%

in horticultural area from 2013 to 2017, statistics.fibl.org) and the partial compensation by successful copper-reduction strategies.

Not surprisingly, as for number of authorized uses, copper use in individual countries correlates with the organic area in which copper use is allowed, which obviously, in turn, is affected by the size of the country, the share of organically managed land, the cultivated crops, and the copper authorizations in these crops. In some countries (e.g., Germany and Switzerland), considerable efforts to reduce copper inputs at national levels have resulted in a significant reduction of copper use per ha in organic farms in the past decade [19]. In these countries, there is a common understanding that, with the current technology, no substantial further reduction is likely in the main crops, particularly in view of the increasing difficulties due to climate change and invasive diseases [19]. In other countries where systematic reduction strategies have been initiated later than in Germany (e.g., Italy, Spain, and France), our experts and other studies assume that the reduction potential might not yet be fully exploited, especially in crops such as olives and nuts [21].

This study shows that, at a European scale, olives, grapevine, and nuts are the main drivers of overall copper use in organic farming, while crops such as apples, pears, and potatoes play a rather minor role. A plausibility check using estimates of Katsoulas et al. [21] indicates that our estimates for olives presented here are rather conservative and that real copper use in olives might even be higher, with a significant impact on overall European copper use. While grapevine is widely known as a main copper-consuming crop [2,6,12,14,37,38], the importance of olives and nuts has not been well documented so far and was quite unexpected for many experts. This might result from the fact that these crops can only be cultivated in relatively few Mediterranean countries, and from the rapid growth of the organic production area in these countries (Supplementary Materials Table S4). For example, in the countries studied, organically managed area for olives and nuts increased 2.4-fold and 7.8–fold, respectively, between 2004 and 2017. Other crops, such as potatoes, which are generally considered to be very copper-intensive, contributed little to total copper consumption, probably due to the relatively small area under cultivation (e.g., potatoes equal 0.65% of the total organically farmed area in the countries studied) and considerable efforts to reduce copper use. Nevertheless, these crops may be important for copper consumption in certain countries, e.g., for potatoes in Belgium, Germany, Switzerland, and the United Kingdom.

4.3. Copper-Replacement Strategies

In view of the considerable amounts of copper to be replaced, it is evident that only a consequent combination of all preventive measures and new alternative products can be successful. The consequent exploitation of preventive measures is a core principle of organic farming that is reflected in the EU regulations ((EC) No. 2018/848, ref. [39]), the guidelines of FAO/WHO [40], and the private standards of IFOAM [41] and farmer associations. For example, the use of disease-resistant cultivars and, more recently, the use of rain shelters in horticultural crops are efficient component strategies for copper reduction [42,43] that are exploited to different degrees depending on crops/countries. The availability of resistant cultivars is a key factor in helping copper reduction. For example, large differences in copper dependency were described for different olive varieties having different levels of susceptibility to diseases [21], and considerably lower amounts of copper are used in more resistant grapevine (PiWi) varieties [18,44,45]. For example, Swiss organic farmers, on average, only use 13% of the maximally allowed copper amounts in PiWi varieties, in comparison to 73% in traditional susceptible varieties [18]. In the Netherlands, where the use of copper as a plant-protection product is not allowed, the yield of organic potato per ha could be increased by 80% by introducing new resistant potato varieties [46]. In many countries, efforts are currently being made to open up markets for new resistant/tolerant varieties. However, preferences of consumers and/or retailers concerning variety and related quality attributes often dictate what farmers should produce (see review by Nuijten et al. [47]). Consequently, the potential market of resistant/tolerant varieties has not yet been fully exploited in many crops/countries. Overall, a successful market introduction of new varieties requires strategies that are tailored to the specific context encompassing the entire supply chain from breeder to consumer [47]. The adoption of preventive strategies (e.g., planting of robust varieties in perennial crops and use of rain shelters) is often costly, time-consuming, and risky for farmers if the market is not receptive [48]. Furthermore, changes of production systems may trigger the emergence of currently minor or secondary diseases or the development of virulent pathogen strains that may overcome varietal resistance. The first phenomenon was observed when apple scab –resistant cultivars were planted at scale: the consequent reduction of fungicides against the main pathogen let previously irrelevant diseases, such as *Diplocarpon mali*, become important [49]. In the second case, for example, new pathogenic races of apple scab–overcoming resistance genes were continuously emerging [50].

Even if all preventive crop-protection strategies are implemented, there is still a significant need for alternative plant-protection products to substitute copper. There are several alternative products available (as summarized in Supplementary Materials Table S1 and by Andrivon and Savini [20] and Dagostin et al. [51]), but none can compete with copper in terms of spectrum of activity, efficacy, and price for growers. While some products with acceptable-to-good efficacy are available for the control of ascomycetes and basidiomycetes (e.g., sulfur, aluminum sulfate, potassium hydrogen carbonate, and lime sulfur), the control of oomycetes and bacteria is provided only to a limited extent by some products. Therefore, crop protection in plants with a wide range of bacterial diseases (e.g., hazelnut, walnut, and oranges) still heavily depends on copper-based plant-protection products. However, the national experts of this survey assess that the potential of available alternatives is probably not fully exploited in some crops, such as olives or nuts, which are often grown with traditional methods, where comparably little effort has been invested into the development of novel strategies. Therefore, efforts to reduce copper use in these crops should be intensified.

The urgent need for highly active fungicidal compounds of natural origin has been recognized (e.g., Dagostin et al. [51]), and systematic screenings for novel compounds were initiated by several research groups, as well as the industry. Promising new plant-protection product candidates include an extract from *Larix decidua* [52], the monosaccharide tagatose derived from lactose [53]; an extract from liquorice (*Glycyrrhiza glabra*) [54]; and a pelargonic acid–based product [55]. Furthermore, refined inorganic compounds, such as calcium carbonate or calcium hydroxide, have been further developed for this aim. If the alternatives are botanical extracts, upscaling to the staggering quantities needed will be a major challenge, while micro-organisms are generally more readily up-scaled in large fermenters [56]. The evaluation and further development of alternatives represented an integral part of several EU-funded projects (e.g., RELACS (https://relacs-project.eu/), FORESTSPECS (https://cordis.europa.eu/project/id/227239/reporting), PROLARIX (https://www.prolarix.eu/homepage.html), CO-FREE (http://www.co-free.net/), and ORGANIC PLUS (https://organic-plus.net/)) (all accessed on 7 March 2022). Even though the most advanced compounds show promising levels of efficacy and seem to cover different uses, none of these alternatives has been authorized as a plant-protection product so far in the EU. The EU has a long and complex procedure to authorize the placing on the market of novel plant-protection products, which requires substantial efforts and investments [56]. This process guarantees citizens and consumers that plant-protection products do not pose substantial risks for health and environment. However, current procedures for bioprotection products (including biocontrol organisms and botanicals) in the EU have evolved from regulations for synthetic active substances. The current lack of specialist bioprotection regulatory body, legislation, procedure, and data requirements is made responsible for the low number of plant-protection products of natural origin placed on the market [57]. The International Biocontrol Manufacturers Association (IBMA) therefore proposes that the EU, for example, establish a bioprotection-specific body and encourages the development of tailored data requirements to facilitate market introduction of products of natural origin [57], which are important tools to reduce copper use and thus to contribute to the implementation of the Sustainable Use of Pesticides Directive of the European Union [58].

5. Conclusions

Organic farming is a rapidly growing market and has clearly left the status of niche production. The environmentally friendly production of healthy food ("Farm2Fork" strategy, https://ec.europa.eu/food/horizontal-topics/farm-fork-strategy_en) (accessed on 7 March 2022) is even at the heart of the European Green Deal that was set out to make Europe the first climate-neutral continent by 2050 (https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en) (accessed on 7 March 2022). However, climate change and invasive pathogens will increase the risk of crop losses due to existing and emerging diseases. To many of these, copper still provides a workable and affordable solution; in view of the staggering amount of copper to be replaced, the scalability of production of alternative plant-protection products is crucial. As copper alternatives will most likely be more expensive than the status quo, roadmaps that facilitate the transition to a no- or low-copper strategy need to be developed. Our survey clearly highlights the need of a centralized database on real use of plant-protection products per crop, disease, and year, which would allow monitoring the success of copper-reduction strategies.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agronomy12030673/s1. Table S1: Current plant-protection situation for selected crops with high importance in European countries. Table S2: Approval of copper compounds as active substances in different European countries. Table S3: Organically managed horticultural area (temperate fruits; grapes; olives; nuts; and vegetables, including potatoes) in 2017 in Europe, in the twelve surveyed countries, and in the three European countries with the largest organically managed area (Spain, Italy, and France). Table S4: Development of the organic area between 2004 and 2017 for crops and countries with the highest annual copper consumption.

Author Contributions: Conceptualization, L.T.; data curation, L.T., B.T. and J.H.-R.; formal analysis, L.T. and B.T.; funding acquisition, L.T.; investigation, L.T., S.A., H.B., E.B., P.E.C., S.F., M.d.P., A.D., C.E., É.A.M., Á.M.P., I.P., A.R., H.S., A.V., H.W. and J.H.-R.; methodology, L.T. and J.H.-R.; project administration, L.T. and J.H.-R.; validation, L.T.; visualization, B.T.; writing—original draft, L.T. and B.T.; writing—review and editing, I.P. and J.H.-R. All authors have read and agreed to the published version of the manuscript.

Funding: This survey was performed within the EU Project RELACS—"Replacement of Contentious Inputs in Organic Farming Systems" (RELACS)—with funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No. 773431.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data files are provided on https://github.com/BarbaraThuerig/copper-use, accessed on 9 March 2022. An earlier version of this manuscript was deposited on a preprint server (https://doi.org/10.31220/agriRxiv.2021.00108) (accessed on 9 March 2022).

Acknowledgments: We gratefully acknowledge Bernhard Speiser (FiBL) for critically reviewing the manuscript.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Ayres, P.G. Alexis Millardet: France's forgotten mycologist. *Mycologist* **2004**, *18*, 23–26. [CrossRef]
2. Gessler, C.; Pertot, I.; Perazzolli, M. *Plasmopara viticola*: A review of knowledge on downy mildew of grapevine and effective disease management. *Phytopathol. Mediterr.* **2011**, *50*, 3–44.
3. Speiser, B.; Schärer, H.-J.; Tamm, L. Direct plant protection in organic farming. In *Improving Organic Crop Cultivation*; Burleigh Dodds Science Publishing: Cambridge, UK, 2018; pp. 1–21.

4. Agrios, G.N. *Plant Pathology*, 5th ed.; Elsevier Academic Press: Burlington, MA, USA, 2005.
5. Tamm, L.; Speiser, B. Direct control of airborne diseases. In *Plant Diseases and Their Management in Organic Agriculture*; Finckh, M.R., van Bruggen, A.H., Tamm, L., Eds.; APS Press: St. Paul, MN, USA, 2015.
6. Lamichhane, J.R.; Osdaghi, E.; Behlau, F.; Köhl, J.; Jones, J.B.; Aubertot, J.-N. Thirteen decades of antimicrobial copper compounds applied in agriculture. A review. *Agron. Sustain. Dev.* **2018**, *38*, 28. [CrossRef]
7. FRAC. FRAC Classification of Fungicides—Fungal Control Agents by Cross Resistance Pattern and Mode of Action 2021. Available online: https://www.frac.info/ (accessed on 22 February 2022).
8. European Commission. 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. 2008. Available online: http://data.europa.eu/eli/reg/2008/889/oj (accessed on 7 March 2022).
9. EFSA Panel on Additives and Products or Substances Used in Animal Feed. Revision of the currently authorised maximum copper content in complete feed. *EFSA J.* **2016**, *14*, e04563. [CrossRef]
10. Finckh, M.; Tamm, L. Organic management and airborne diseases. In *Plant Diseases and Their Management in Organic Agriculture*; Finckh, M.R., van Bruggen, A.H., Tamm, L., Eds.; APS Press: St. Paul, MN, USA, 2015; pp. 53–65.
11. Panagos, P.; Ballabio, C.; Lugato, E.; Jones, A.; Borrelli, P.; Scarpa, S.; Orgiazzi, A.; Montanarella, L. Potential sources of anthropogenic copper inputs to European agricultural soils. *Sustainability* **2018**, *10*, 2380. [CrossRef]
12. Ballabio, C.; Panagos, P.; Lugato, E.; Huang, J.-H.; Orgiazzi, A.; Jones, A.; Fernández-Ugalde, O.; Borrelli, P.; Montanarella, L. Copper distribution in European topsoils: An assessment based on LUCAS soil survey. *Sci. Total Environ.* **2018**, *636*, 282–298. [CrossRef]
13. La Torre, A.; Iovino, V.; Caradonia, F. Copper in plant protection: Current situation and prospects. *Phytopathol. Mediterr.* **2018**, *57*, 201–236. [CrossRef]
14. Karimi, B.; Masson, V.; Guilland, C.; Leroy, E.; Pellegrinelli, S.; Giboulot, E.; Maron, P.-A.; Ranjard, L. Ecotoxicity of copper input and accumulation for soil biodiversity in vineyards. *Environ. Chem. Lett.* **2021**, *19*, 2013–2030. [CrossRef]
15. European Commission. Commission Implementig Regulation (EU) 2018/1981 of 13 December 2018 Renewing the Approval of the Active Substances Copper Compounds, as Candidates for Substitution, in Accordance with Regulation (EC) No 1107/2009 of the European Parliament and of the Council Concerning the Placing of Plant Protection Products on the Market, and Amending the Annex to Commission Implementing Regulation (EU) No 540/2011. 2018. Available online: http://data.europa.eu/eli/reg_impl/2018/1981/oj (accessed on 7 March 2022).
16. European Commission. Consolidated Text: Commission Implementing Regulation (EU) No 540/2011 of 25 May 2011 Implementing Regulation (EC) No 1107/2009 of the European Parliament and of the Council as Regards the List of Approved Active Substances (Text with EEA relevance). Available online: http://data.europa.eu/eli/reg_impl/2011/540/oj (accessed on 7 March 2022).
17. European Commission. Commission Implementing Regulation (EU) 2021/1165 of 15 July 2021 Authorising Certain Products and Substances for use in Organic Production and Establishing Their Lists. 2021. Available online: http://data.europa.eu/eli/reg_impl/2021/1165/oj (accessed on 7 March 2022).
18. Speiser, B.; Mieves, E.; Tamm, L. Kupfereinsatz von Schweizer Biobauern in verschiedenen Kulturen. *Agrar. Schweiz* **2015**, *6*, 160–165.
19. Kühne, S.; Roßberg, D.; Röhrig, P.; von Mehring, F.; Weihrauch, F.; Kanthak, S.; Kienzle, J.; Patzwahl, W.; Reiners, E.; Gitzel, J. The use of copper pesticides in Germany and the search for minimization and replacement strategies. *Org. Farming* **2017**, *3*, 66–75. [CrossRef]
20. Andrivon, D.; Savini, I. *Peut-On se Passer du Cuivre en Protection des Cultures Biologiques? Synthèse du Rapport D'expertise Scientifique Collective*; INRA: Paris, France, 2018; p. 66.
21. Katsoulas, N.; Løes, A.-K.; Andrivon, D.; Cirvilleri, G.; de Cara, M.; Kir, A.; Knebl, L.; Malińska, K.; Oudshoorn, F.; Willer, H. Current use of copper, mineral oils and sulphur for plant protection in organic horticultural crops across 10 European countries. *Org. Agric.* **2020**, *10*, 159–171. [CrossRef]
22. Finckh, M.R.; van Bruggen, A.H.; Tamm, L. (Eds.) *Plant Diseases and Their Management in Organic Agriculture*, 1st ed.; APS Press: St. Paul, MN, USA, 2015; p. 414.
23. Bouma, E. Development of comparable agroclimatic zones. *Bull. OEPP/EPPO Bull.* **2005**, *35*, 233–238. [CrossRef]
24. Willer, H.; Lernoud, J. *The World of Organic Agriculture: Statistics and Emerging Trends 2019*; Research Institute of Organic Agriculture FiBL & IFOAM Organics International: Frick, Switzerland, 2019.
25. European Commission. EU Pesticides Database. Available online: https://ec.europa.eu/food/plants/pesticides/eu-pesticides-database_en (accessed on 7 March 2022).
26. European and Mediterranean Plant Protection Organisation EPPO. List of Databases on Registered Plant Protection Products in the EPPO Region. Available online: https://www.eppo.int/ACTIVITIES/plant_protection_products/registered_products (accessed on 22 February 2022).
27. DG SANCO. Working Document on Emergency Situations According to Article 53 of Regulation (EC) No 1107/2009. 2013. Available online: https://www.legislation.gov.uk/eur/2009/1107/contents# (accessed on 7 March 2022).

28. OECD. *Guidance Document on Regulatory Incentives for the Registration of Pesticide Minor Uses*; OECD Publishing: Paris, France, 2014. [CrossRef]
29. European Parliament and the Council. Regulation (EC) No 1107/2009 of the European Parliament and of the Council of 21 October 2009 Concerning the Placing of Plant Protection Products on the Market and Repealing Council Directives 79/117/EEC and 91/414/EEC. 2009. Available online: http://data.europa.eu/eli/reg/2009/1107/oj (accessed on 7 March 2022).
30. Biodynamic Federation Demeter. *Production, Processing and Labelling: International Standard for the Use and Certification of Demeter, Biodynamic and Related Trademarks (As of: July 2020/1st Circulation)*; Biodynamic Federation: Darmstadt, Germany, 2021.
31. European Parliament and the Council. Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 Laying Down Rules on the Making Available on the Market of EU Fertilising Products and Amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and Repealing Regulation (EC) No 2003/2003. 2019. Available online: http://data.europa.eu/eli/reg/2019/1009/oj (accessed on 7 March 2022).
32. Sabatino, L.; Scarangella, M.; Lazzaro, F.; Scordino, M.; Picariello, G.; Leotta, C.; Traulo, P.; Gagliano, G. Matrine and oxymatrine in corroborant plant extracts and fertilizers: HPLC/MS-MS method development and single-laboratory validation. *J. Environ. Sci. Health Part B* **2015**, *50*, 862–870. [CrossRef] [PubMed]
33. Research Insitute of Organic Agriculture FiBL. European Input List. Available online: https://www.inputs.eu/ (accessed on 22 February 2022).
34. Varga, K.; Fehér, J.; Trugly, B.; Drexler, D.; Leiber, F.; Verrastro, V.; Magid, J.; Chylinski, C.; Athanasiadou, S.; Thuerig, B.; et al. The state of play of copper, mineral oil, external nutrient input, anthelmintics, antibiotics and vitamin usage and available reduction strategies in organic farming across Europe. *Sustainability* **2022**, *14*, 3182. [CrossRef]
35. Mesnage, R.; Straw, E.A.; Antoniou, M.N.; Benbrook, C.; Brown, M.J.F.; Chauzat, M.-P.; Finger, R.; Goulson, D.; Leadbeater, E.; López-Ballesteros, A.; et al. Improving pesticide-use data for the EU. *Nat. Ecol. Evol.* **2021**, *5*, 1560. [CrossRef]
36. Tamm, L.; Speiser, B.; Niggli, U. Reduktion von Pflanzenschutzmitteln in der Schweiz: Beitrag des Biolandbaus. *Agrar. Schweiz* **2018**, *9*, 52–59.
37. Pietrzak, U.; McPhail, D. Copper accumulation, distribution and fractionation in vineyard soils of Victoria, Australia. *Geoderma* **2004**, *122*, 151–166. [CrossRef]
38. Ruyters, S.; Salaets, P.; Oorts, K.; Smolders, E. Copper toxicity in soils under established vineyards in Europe: A survey. *Sci. Total Environ.* **2013**, *443*, 470–477. [CrossRef]
39. European Parliament and the Council. 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. 2018. Available online: http://data.europa.eu/eli/reg/2018/848/oj (accessed on 7 March 2022).
40. Codex Alimentarius Commission. *Guidelines for the Production, Processing, Labelling and Marketing of Organically Produced Foods*; FAO: Rome, Italy, 2013.
41. IFOAM. *The IFOAM Norms for Organic Production and Processing*; Version 2014; IFOAM-Organics International: Bonn, Germany, 2019.
42. Lang, G.; Sage, L.; Wilkinson, T. Ten years of studies on systems to modify sweet cherry production environments: Retractable roofs, high tunnels, and rain-shelters. *Acta Hortic.* **2016**, *1130*, 83–90. [CrossRef]
43. Kelderer, M.; Casera, C.; Lardschneider, E.; Telfser, J. Field trials in apple orchards with different covering methods to reduce plant protection treatments and yield losses due to pests and diseases. In Proceedings of the 18th International Conference on Organic Fruit-Growing, online, 19–21 February 2018; pp. 64–70.
44. Casanova-Gascón, J.; Ferrer-Martín, C.; Bernad-Eustaquio, A.; Elbaile-Mur, A.; Ayuso-Rodríguez, J.M.; Torres-Sánchez, S.; Jarne-Casasús, A.; Martín-Ramos, P. Behavior of vine varieties resistant to fungal diseases in the Somontano Region. *Agronomy* **2019**, *9*, 738. [CrossRef]
45. Rousseau, J.; Chanfreau, S.; Bontemps, É. *Les Cépages Résistants and Maladies Cryptogamiques*; Groupe ICV: Bordeaux, France, 2013; p. 228.
46. Keijzer, P.; van Bueren, E.T.L.; Engelen, C.J.M.; Hutten, R.C.B. Breeding late blight resistant potatoes for organic farming—a collaborative model of participatory plant breeding: The Bioimpuls Project. *Potato Res.* **2021**. [CrossRef]
47. Nuijten, E.; de Wit, J.; Janmaat, L.; Schmitt, A.; Tamm, L.; van Bueren, E.T.L. Understanding obstacles and opportunities for successful market introduction of crop varieties with resistance against major diseases. *Org. Agric.* **2018**, *8*, 285–299. [CrossRef]
48. Tamm, L.; Häseli, A.; Fuchs, J.G.; Weibel, F.P.; Wyss, E. Organic fruit production in humid climates of Europe: Bottlenecks and new approaches in disease and pest control. *Acta Hortic.* **2004**, *638*, 333–339. [CrossRef]
49. Wöhner, T.; Emeriewen, O.F. Apple blotch disease (*Marssonina coronaria* (Ellis & Davis) Davis)—Review and research prospects. *Eur. J. Plant Pathol.* **2019**, *153*, 657–669. [CrossRef]
50. Belete, T.; Boyraz, N. Critical review on apple scab (*Venturia inaequalis*) biology, epidemiology, economic importance, management and defense mechanisms to the causal agent. *J. Plant Physiol. Pathol.* **2017**, *5*, 2. [CrossRef]
51. Dagostin, S.; Schärer, H.-J.; Pertot, I.; Tamm, L. Are there alternatives to copper for controlling grapevine downy mildew in organic viticulture? *Crop Prot.* **2011**, *30*, 776–788. [CrossRef]
52. Thuerig, B.; James, E.E.; Schärer, H.-J.; Langat, M.K.; Mulholland, D.A.; Treutwein, J.; Kleeberg, I.; Ludwig, M.; Jayarajah, P.; Giovannini, O.; et al. Reducing copper use in the environment: The use of larixol and larixyl acetate to treat downy mildew caused by *Plasmopara viticola* in viticulture. *Pest Manag. Sci.* **2018**, *74*, 477–488. [CrossRef]

53. Ohara, T.; Ishida, Y.; Kudou, R.; Kakibuchi, K.; Akimitsu, K.; Izumori, K. Plant disease control agent comprising D-tagatose as active ingredient, and plant disease control method. U.S. Patent 9,125,409, 9 September 2015.
54. Scherf, A.; Treutwein, J.; Kleeberg, H.; Schmitt, A. Efficacy of leaf extract fractions of *Glycyrrhiza glabra* L. against downy mildew of cucumber (*Pseudoperonospora cubensis*). *Eur. J. Plant Pathol.* **2012**, *134*, 755–762. [CrossRef]
55. Liu, X.; Han, R.; Wang, Y.; Li, X.; Zhang, M.; Yan, Y. Fungicidal activity of a medium-chain fatty acids mixture comprising caprylic, pelargonic and capric acids. *Plant Pathol. J.* **2014**, *13*, 65–70. [CrossRef]
56. Thuerig, B.; Tamm, L. Development of plant-derived compounds as biopesticides. In *Biopesticides for Sustainable Agriculture*; Birch, N., Glare, T., Eds.; Burleigh Dodds Science Publishing: Cambridge, UK, 2020; pp. 315–334.
57. IBMA. *IBMA White Paper—New EU Regulatory Framework for Bioprotection Agents: IBMA Vision on How to Improve Regulation in the European Union*; International Biocontrol Manufacturer Association (IBMA): Brussels, Belgium, 2018.
58. European Parliament and the Council. Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009. Establishing a Framework for Community Action to Achieve the Sustainable use of Pesticides. Available online: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02009L0128-20091125&qid=1480935685846&from=de (accessed on 9 December 2016).