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Review

Literature review: Impact of climate change on pesticide use

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ABSTRACT

Agricultural yields strongly depend on crop protection measures. The main purpose of pesticide use is to increase food security, with a secondary goal being increased standard of living. In view of a changing climate, not only crop yields but also pesticide use is expected to be affected. Therefore, an analysis of the detailed effect of changing climatic variables on pesticide use is conducted. Not only effects on cultivated crops, occurring pests and pesticide efficiency are considered but also implications for technological development, regulations and the economic situation are included as all of these aspects can influence pesticide use. The objective of this review is to gain insights into the specific effect of climate change on the consumer exposure caused by pesticide residues on crops. In terms of climate change, temperature increase and changes in precipitation patterns are the main pest and pathogen infection determinants. An increased pesticide use is expected in form of higher amounts, doses, frequencies and different varieties or types of products applied. Climate change will reduce environmental concentrations of pesticides due to a combination of increased volatilization and accelerated degradation, both strongly affected by a high moisture content, elevated temperatures and direct exposure to sunlight. Pesticide dissipation seems also to be benefitted by higher amounts of precipitation. To overcome this, pesticide use might be changed. An adapted pesticide use will finally impact consumer exposure at the end of the food chain.

Contents

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1. Introduction

Climate change is defined as a change in the statistical properties of the climate system, when considered over long periods of time, regardless of cause (ENSAA, 2011; IPCC, 2001). There is concordance amongst scientists that climate change encompasses atmospheric carbon dioxide variations, altered worldwide temperatures and precipitation variation, all directly or indirectly influencing sea levels and salinity, alterations in arable land, crop yields, changes in soil quality, nitrogen deposition and plant diversity (Fontaine, Decker, & Skagen, 2009; Harvell et al., 2002; Jackson et al., 2011; Miraglia et al., 2009). The extensively differing impact on nature, human health and even the economy, implies that climate change is both spatially and temporally heterogeneous (EEA, 2012; Fontaine et al., 2009; Harvell et al., 2002).

Temperature, light and water are the key elements that control the growth and development of organisms (Harvell et al., 2002; Rosenzweig, Iglesias, Yang, Epstein, & Chivian, 2001). Consequently, biodiversity responses that depend on these environmental parameters, can be expected (Lepetz, Massot, Schmeller, & Clobert, 2009). For example, altered precipitation patterns and cultivation practices can create a thriving environment for insect and pathogen attacks (Roos, Hopkins, Kvarnheden, & Dixelius, 2011), or corresponding advances in phenology (Fontaine et al., 2009). Moreover, the increasing climate variability (Wang, Zwiers, Swail, & Feng, 2009) can induce alterations in interspecific relationships between organisms, such as competition or predation (Lepetz et al., 2009), possibly resulting in a decrease in food supplies and an increase in microbial and toxic contaminants in food (Hall, D Souza, & Kirk, 2002).

For several decades, pesticides have been widely used to prevent, mitigate or destroy pests and improve commodities' yield and quality. Their mode of action provides a competitive advantage for agricultural crops, in comparison with weeds and protects the crops from the damaging influences of pests and diseases. Despite the potential toxicity for beneficial organisms and even human health, their use is a necessity to retain the current production yields and high quality life standards. Pesticide efficiency and use can be influenced in many ways and not in the least by environmental conditions. Given the general acceptance of major climate change effects, it is obvious that an effect on pesticide use can also be expected. The direction of this effect is, however, uncertain and has not yet been thoroughly investigated. Research for the effects of climate change, is generally not limited to pesticides and consequently, not very detailed, in a way that only limited influencing factors or effects are described. Climate change has a powerful effect on the environmental fate and behaviour of pesticides by altering fundamental mechanisms of partitioning between the environmental compartments, also affecting pesticide use (Noyes et al., 2009). A lower pesticide residue on crops, due to climate change, results in an increased vulnerability to pests and diseases, meaning that in the future, farmers may have to spray more often during the growing season. A higher pest or disease pressure will also enhance application frequencies and volumes. As a consequence, the detected residue concentrations might double for some products, while others will disappear faster and hence, do not increase the residues on crops. In this review, the current knowledge of possible climate change effects on pesticide use was combined and a detailed effect on pesticide use was distilled. The importance of this effect, lies in the implications of an adapted pesticide use for consumer exposure to pesticide residues at the end of the food supply chain.

In contrast to natural contaminants, produced by micro-organisms or fungi, pesticide residues in food, can be controlled by human actions. Highly toxic crop protection chemicals can, for instance, be replaced by less dangerous or more human and environmental friendly alternatives. In this respect, the food safety issues related to an increased exposure to pesticide residues, as a consequence of climate change, might not occur.

2. Influencing factors for pesticide use

Given the multivariate nature of climate change and nonlinear thresholds in natural processes, it is difficult to consider all the links between climate change and pesticide use (Harvell et al., 2002). Six aspects that directly impact a farmer's use of pesticides, were selected (Fig. 1). Amongst those six aspects, legislation, the economic situation and technological progress are not directly influenced by climate, while pesticide efficiency, crop characteristics and pest occurrence and severity are directly influenced by climate. Interactions between those six key aspects and pesticide use, are discussed in detail in the following paragraphs.

2.1. Legislation, economic situation and technological progress

Pesticide use is strongly controlled through several Regulations, included in legislation, which define the authorized active substance/crop combinations. The concentration of pesticide residues that may remain on the crops after harvest, is regulated by setting Maximum Residue Levels (MRLs). At the national level, legislation is, consequently,

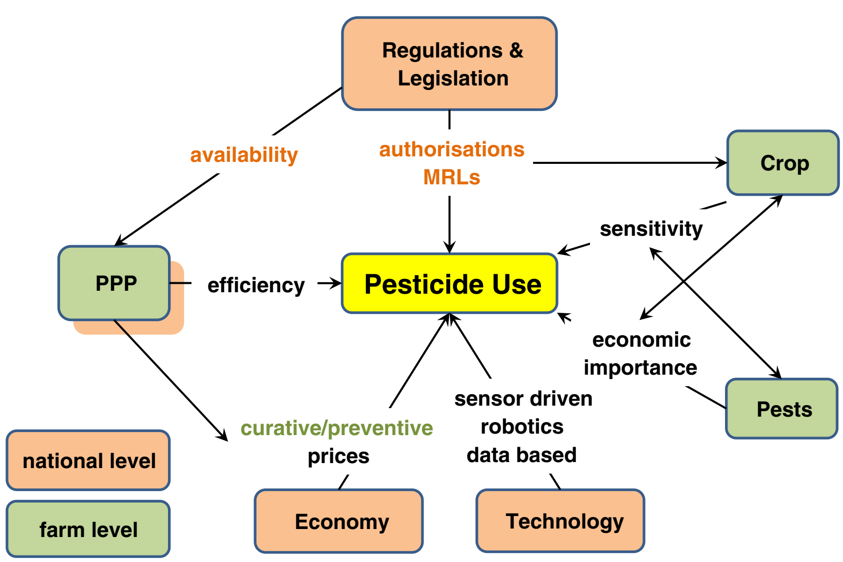

Fig. 1. Influencing factors for pesticide use and the level at which they have an effect (national or farm level). (PPP = Plant Protection Product, MRL = Maximum Residue Limit.)

an important influencing factor for pesticide use, as it clearly limits the number and scope of pesticides a farmer has at his disposal.

With regard to the economic situation, Eid, El-Marsafawy, and Ouda (2007) indicated that high temperatures can constrain agricultural production. Additionally, Turner, Longstreth, Johnson, and Rosenberg (1994) have shown that a shift in precipitation can also slow down the economic development of some nations and particularly affects agricultural production. The economic climate also strongly influences on-farm decisions, by limiting farmers' pest control options. Firstly, pesticide producing companies decide what products, active substances and formulations will be marketed in a specific country. An important issue is the focus on production for major crops, to increase a company's profits. This limits the scope of available products for small-scale crops. Secondly, farmers can use preventive or curative pesticides according to the advice of an officer or seller, but in reality, this choice will largely be influenced by the purchase and application costs. A good example is the use of illegal products or obsolete stocks in developing countries because of the small scope of available products and their high prices (Wassie, 2012).

Technological progress also strongly influences PPP application and residues. An example of advanced agricultural technologies, is the use of GPS guided field sprayers in modern farming systems. These sprayers are equipped with sensors to determine their location and for example, plant numbers, coverage levels, the amount of biomass or infection levels. A combination of the recordings of these robotics, with additional information on required pesticide doses, leads to precision farming, which promotes a more efficient pest/disease control (Dworak et al., 2013). Such targeted applications decrease the required PPP volumes, to maintain the same level of crop protection, in comparison with current practices.

2.2. Pesticide use and crop combination

Pesticide adhesion and uptake into a plant is driven by plant growth and soil properties, both strongly liable to climatic influences. Clearly, all species have characteristic climatic requirements for growth, survival and reproduction that limit their geographic distribution (e.g. need of vernalisation), agricultural value, abundance and interactions with other species (Bloomfield, Williams, Gooddy, Cape, & Guha, 2006; Gutierrez, Ponti, d'Oultremont, & Ellis, 2008; Harvell et al., 2002). Generally, most food crops are sensitive to the direct effects of high temperature and precipitation extremes or indirect effects of the climate on soil processes, nutrient dynamics and pest organisms (Rosenzweig et al., 2001).

2.2.1. Temperature and CO_2

Higher temperatures and increased CO_2 concentrations, associated with a substantial change in photosynthetic activity, promote plant growth and expansion (Gutierrez et al., 2008; Reilly et al., 2003). A high growth rate can cause a dilution of the absorbed pesticide concentration in plants, decreasing the pesticide residue (Holland & Sinclair, 2004; Zongmao & Haibin, 1997). In addition, the roots are able to reach deeper soil layers, thus preventing uptake of pesticides, present in the top layers. Contrarily, root uptake is enhanced when the high temperatures cause a decrease in soil organic matter and elevated evaporation rate (Miraglia et al., 2009). Warm and dry conditions can increase resistance to plant infections resulting in a reduced fungicide need (Patterson, Westbrook, Joyce, Lingren, & Rogasik, 1999), which is also the case with high atmospheric CO_2 concentrations (Scherm, 2004). On the contrary, physiological plant stress, especially in sensitive crop developmental stages, increases host susceptibility and pesticide dependency (Harvell et al., 2002; Rosenzweig et al., 2001). This might boost the use of new breeds in the future (Roos et al., 2011). A lengthening of the active growing season potentially allows for increased farming, introduction of new crops and a northward crop expansion. This ability to grow new or more crops might result in increased pesticide use and their introduction in naïve ecosystems (Noyes et al., 2009). On the contrary, a temperature variability increase can adversely affect crops growing at low or high mean temperatures due to diurnal and seasonal canopy temperature fluctuations that exceed the crop's optimum range (Rosenzweig et al., 2001). In conclusion, increased temperatures will affect plant productivity (Rosenzweig et al., 2001; Scherm, 2004; Woodruff et al., 2009), giving rise to a potential increase in volume and array of pesticides used (Noyes et al., 2009) and a shift in cropping patterns exemplified by, for example, a due change in sowing dates (Eid et al., 2007).

2.2.2. Precipitation

Precipitation is the other major determining factor of crop productivity, influencing variations in crop yields, yield quality and pests in both a positive and negative way (Gadgil, Rao, & Rao, 2002; Gutierrez et al., 2008; Patterson et al., 1999; Reilly et al., 2003; Rosenzweig et al., 2001). This duality lies in greater precipitation during the growing season that tends to increase yields, while intense rainfall can damage younger plants and be detrimental to crop productivity (Rosenzweig et al., 2001). Here for, the use of early maturing varieties and crop varieties with high water use efficiency will possibly blossom (Eid et al., 2007; Gadgil et al., 2002). Pesticide uptake and transport in plants, are affected by precipitation and will be limited in case of decreased transpiration under dry circumstances (Keikotlhaile, 2011).

2.2.3. Crop–pest interactions

Climatic variation influences the physiology and phenology of the host species, host resistance and growth, all possibly disrupting the synchrony between host and parasite (Harvell et al., 2002; Perarnaud, Seguin, Malezieux, Deque, & Loustau, 2005; Rosenzweig et al., 2001). In contrast, the most severe and least predictable disease outbreaks might occur when altered geographic ranges cause formerly disjunctive species and populations to converge (Harvell et al., 2002). This effect can even be enhanced in the presence of a maladjusted population of compatible beneficial insects, to diminish the pest infestations (Rosenzweig et al., 2001). Finally, due to cropping intensification, crop rotation reductions, increased areas of perennial crops, introduction of new species or varieties and autumn sowing, the rural landscape changes. These changes influence the location and availability of host plants for pest species and provide a green bridge for pests during winter (Noyes et al., 2009; Reilly et al., 2003; Roos et al., 2011; Rosenzweig et al., 2001).

2.2.4. Adaptation measures

Simulations show that production in developed countries benefit from the projected climate change, whereas production in developing nations is expected to decline (Rosenzweig et al., 2001). In response to climate change and a pronounced decrease in area for specific crops, a change in planting date, shortened maturity dates and an expanded use of better adapted cultivars are decent adaptation measures (Reilly et al., 2003; Shakhramanyan, Schneider, & McCarl, 2013). In addition, the introduction of more genetically modified organisms might be a solution (Hall et al., 2002).

Because of the reduced pesticide tolerance of crops under stress, the use of another range of new pesticides will possibly be needed. On the other hand, a shift in the use of certain classes of current pesticide products is the most probable evolution.

2.3. Occurring pests (weeds, insects and diseases)

In terms of climate change, temperature increases and precipitation changes are the main pest infection determinants. Other influencing aspects are dew, atmospheric CO_2 concentration and radiation (Bloomfield et al., 2006; Jackson et al., 2011; Noyes et al., 2009; Rosenzweig et al., 2001; Scherm, 2004).

Crop damage by pests and diseases is a result of complex ecological dynamics between two or more organisms and is therefore difficult to predict exactly (Rosenzweig et al., 2001; Scherm, 2004). There are indications that climate change causes phenology and geographic distribution changes in a wide range of ecosystems (Greco et al., 2011; Scherm, 2004; Seeland, Oehlmann, & Mueller, 2012). As a result of the expected response of single species and communities to climate change (Müller et al., 2010), a disturbed temporal synchrony of pest, host and bio-control agents with according yield losses is likely (Fontaine et al., 2009; Gutierrez et al., 2008; Patterson et al., 1999; Perarnaud et al., 2005; Scherm, 2004). Research figures out that pest infestations often coincide with modifications in climatic conditions (Rosenzweig et al., 2001), so changes are species and region specific (Noyes et al., 2009).

In general, many pest and pathogen species are favoured by warm and humid conditions, of which the humidity is the main confounding factor affecting crop–pest interactions (Bloomfield et al., 2006; Delorenzo, Wallace, Danese, & Baird, 2009; Rosenzweig et al., 2001).

2.3.1. Insect pests

Although insects flourish in all climates, research reports an earlier appearance and activity in warmer circumstances (Bloomfield et al., 2006; Jackson et al., 2011; Rosenzweig et al., 2001). This is not illogical as temperature affects not only the availability of host plants and refuges, but also improves overwintering, dispersal, migration and population characteristics such as reproduction and growth rates (Jackson et al., 2011; Macdonald, Harner, & Fyfe, 2005; Patterson et al., 1999; Perarnaud et al., 2005; Roos et al., 2011; Rosenzweig et al., 2001). In addition, Harvell et al. (2002) reported a negative correlation between temperature and the severity of fungal pathogens of insects. For instance, a surplus of five generations a year of aphids is expected with climate change (Roos et al., 2011).

Wet conditions bring on severe insect and plant pathogen infestations (Rosenzweig et al., 2001) or effect a geographical shift of some insects (Bloomfield et al., 2006). Increases in CO_2 concentration, wind induced dispersal of pests, differences in soil nitrogen content and population density, determine insect abundance (Patterson et al., 1999; Roos et al., 2011). Finally, extremes seem to have a divergent effect by reducing some species longevity, while others thrive in these circumstances (Perarnaud et al., 2005; Rosenzweig et al., 2001).

In summary, climate change promotes distribution and abundance of pests due to migration and range shifts, increases pest outbreaks and alters the dissemination of vectors (Gutierrez et al., 2008; Hall et al., 2002; Jackson et al., 2011; Macdonald et al., 2005; Midgley, Hannah, Millar, Rutherford, & Powrie, 2002; Miraglia et al., 2009; Noyes et al., 2009), all favouring pests compared to crops (Müller et al., 2010; Roos et al., 2011).

2.3.2. Diseases

Plant diseases are mainly affected by temperature, rainfall, humidity, radiation and dew (Patterson et al., 1999). Plant diseases can be influenced by altering biological processes of the host, pathogen or disease-spreading organisms. Different life stages may vary in their climatic susceptibilities but, the direct effects on pathogens are likely to be strongest (Burdon & Elmqvist, 1996). Wet conditions promote the germination of spores, the spread and activity of zoospores and the proliferation of fungi and bacteria (Roos et al., 2011; Rosenzweig et al., 2001). This is also the case for extreme events and rainfall in particular, which aid the dispersal of diseases (Hall et al., 2002; Jackson et al., 2011).

Directional climate warming effects are expected to improve pathogen overwintering, development and dispersal, all resulting in an elevated disease severity and plant losses (Harvell et al., 2002; Roos et al., 2011). In the case of soil-borne pathogens, a pre-seasonal sclerotial stage was observed after mild winters, leading to more frequent root infections. In addition, these infected plants became more sensitive to above ground pathogens.

Oliveira, Ribeiro, Delgado, and Abreu (2009) demonstrated a season-specific response of fungal spore dispersal and concentration to climate aspects. While *Aspergillus* and *Penicillium* spore concentrations were not affected by meteorological factors, divergent responses were found for other fungi. For example, spring–autumn spores of *Pleospora* were negatively correlated with temperature and positively correlated with relative humidity and rainfall. On the other hand, inverse correlations of late spring till summer spores of *Alternaria* with the respective climate elements, were recorded. Single abiotic stress factors also seem to impact fungal diseases differently compared to when they are combined. Other climate effects are seen for pathogens causing overwintering diseases. Due to milder winters and less snow cover, the importance of these pathogens can decrease. Late blight incidence on potato on the other hand, is expected to increase in the case of warmer springs, summers and more humid conditions of the future. The main cause is a shift to populations with greater spore production capacity and shorter infection to symptom interval (Roos et al., 2011). Moreover, these short generation times permit a quick adaptation of the fungus to increased host resistance (Scherm, 2004).

Obviously, it is difficult to completely seize the links between climate and disease processes given the high degree of complexity in plant–pathogen systems and nonlinear thresholds in both (Harvell et al., 2002; Roos et al., 2011). Nevertheless, an increased disease pressure is expected to contribute to population declines, especially for pathogens infecting multiple host species (Harvell et al., 2002).

2.3.3. Weeds

Because of the susceptibility of the crop–weed interactions, local environmental factors benefit either crop or weed (Jackson et al., 2011). A temperature increase appears to cause fundamentally altered weed communities and a geographic niche expansion of many species (Jackson et al., 2011; Patterson et al., 1999). Research also demonstrated that an increased atmospheric CO_2 concentration directly increased weeds' herbicide tolerance and severity (Gutierrez et al., 2008) because of the higher carbon dioxide fertilization effect and improved water use efficiency in comparison with agricultural crops (Patterson et al., 1999; Rosenzweig et al., 2001). In addition, increasing leaf thickness and the partial stomatal closure in this case, reduce herbicide absorption and efficacy (Jackson et al., 2011).

2.3.4. Pesticide use

The challenge of pests to agriculture will rise due to increased prevalences of pests, diseases and weeds, which affect pesticide activity (Miraglia et al., 2009; Müller et al., 2010; Ntonifor, 2011; Patterson et al., 1999). In the past, application rates and total amounts of herbicides exceeded insecticides or fungicides (Probst, Berenzen, Lentzen-Godding, & Schulz, 2005), which will probably shift because of the pest population favouring climate changes (Goel, McConnell, & Torrents, 2005). Nevertheless, weed resistance to herbicides and the according decline in efficacy can influence the balance (Bailey, 2003). A compensatory increased use of agricultural chemicals in general, seems necessary (Hall et al., 2002; Rosenzweig et al., 2001). In the first instance, a shorter infection–symptom interval causes the need for more frequent pesticide sprayings to prevent infection (Noyes et al., 2009; Roos et al., 2011). Secondly, the augmented evolutionary rate of genetically different strains and according quick pesticide resistance development under warm conditions, might be insufficiently covered by current pest management strategies (Jackson et al., 2011). Improved biological control tools will become a solution for populations that are resistant to pesticides (Jackson et al., 2011).

In developing countries, easily available, biodegradable, low cost and low risk pesticides are needed for low income peasant farmers and organic farmers (Ntonifor, 2011). This is important since it is expected that these countries may suffer most form climate change. Some countries might even re-introduce or increase the use of banned or restricted pesticides (Macdonald et al., 2005).

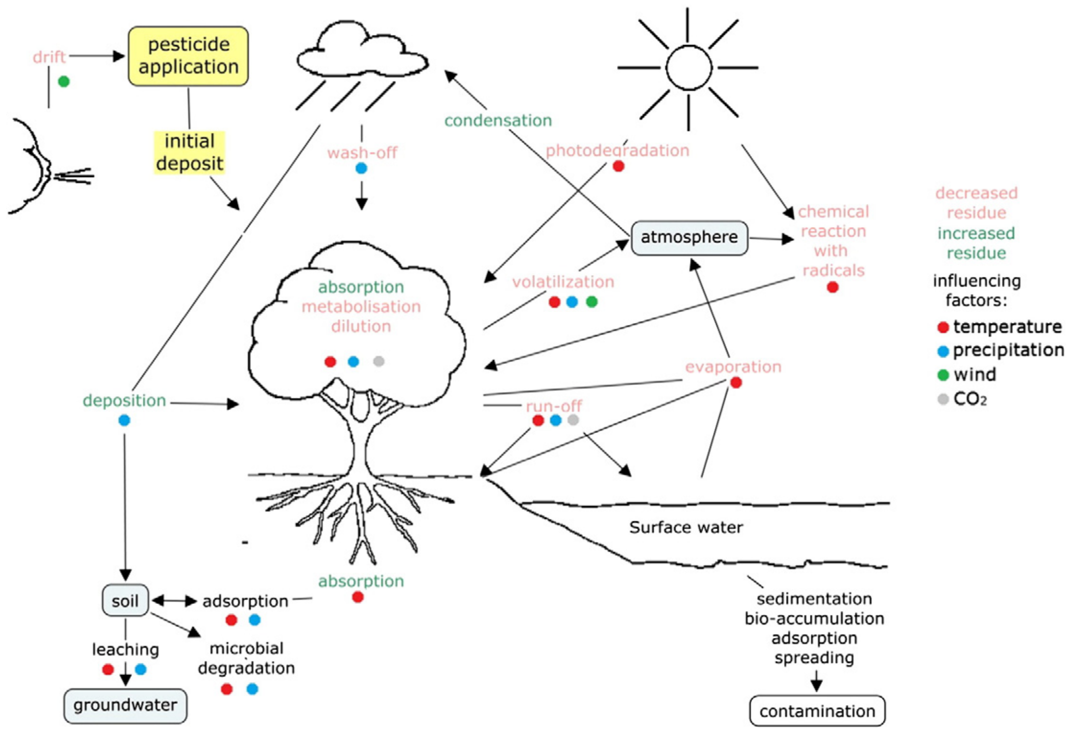

Fig. 2. Illustration of the environmental factors that influence pesticide fate after application.

2.4. Fate of pesticides (PPP)

The level of plant protection is determined by the pesticide residue level on that plant, which is in turn influenced by a product's formulation, concentration, dose and application method. A pesticide can interact with the plant surface, but is also exposed to environmental influences such as wind, sun radiation and rainfall (Keikotlhaile, 2011; Steurbaut, 2009). Pesticide transport and degradation are the two main routes that affect pesticide availability and efficacy. In the case of systemic products, transfer inside plants is essential for pest control (Keikotlhaile, 2011). Pesticide transfer includes volatilization, wash- and runoff and leaching processes, while pesticide degradation encompasses photolysis, chemical and microbial breakdown (Fig. 2). Next to pesticide dissipation, pesticide ecotoxicity will also determine the efficacy of an applied dose and consequently, influence pesticide use.

2.4.1. Pesticide transport and climate change

2.4.1.1. Volatilization. Volatilization from soil and vegetation is one of the main causes of pesticides in the atmosphere (Yeo, Choi, Chun, & Sunwoo, 2003) and takes place when a liquid or solid substance transfers to the gaseous phase. In climatic terms, rapid volatilization is mainly due to elevated temperatures, direct exposure to sunlight and a high soil moisture content (Johnson, Wauchope, & Burgoa, 1995; Otieno, Owuor, Lalah, Pfister, & Schramm, 2013). Unfortunately, an unambiguous climate change effect on the exchange processes at the interface of the air, soil and vegetation cannot be characterized (van Pul et al., 1999). This is exemplified by Bossi et al. (2008), who noted no clear seasonal variation in the concentrations of organochlorine pesticides, while van Dijk and Guicherit (1999) pointed out that this was actually the case for more persistent pesticides.

Studies in the USA and Korea reported higher volatilization rates of organochlorine pesticides during warmer weather (Nations & Hallberg, 1992; Yeo et al., 2003). In spite of an opposite result for fenhexamid (Schummer et al., 2010), this finding has more recently been confirmed for other substances, of which the atmospheric concentrations show a significant positive correlation with temperature (Bloomfield et al., 2006; Holland & Sinclair, 2004; Navarro, Vela, & Navarro, 2007; Steurbaut, 2009). Bossi et al. (2008) showed that a temperature induced re-emission of compounds from previously contaminated surfaces can also occur. A humid soil after rainfall, similar to temperature, favours pesticide volatilization (Navarro et al., 2007), while research on the effect of relative humidity did not record any correlation (Schummer et al., 2010).

After volatilization, compounds can be dispersed (van Dijk & Guicherit, 1999) from areas with high concentrations and be distributed widely at low concentrations in the form of aerial inputs or wet deposition in rain (Bloomfield et al., 2006; De Rossi, Bierl, & Riefstahl, 2003; Donald, Cessna, Sverko, & Glozier, 2007; Dubus, Hollis, & Brown, 2000; Polkowska et al., 2000; van Dijk & Guicherit, 1999). Characteristics of this wet deposition are an elevated concentration of residues in rain at the beginning of the rain event (Goel et al., 2005) and an increased amount of contaminants due to higher intensity and frequency rain and storm events (Noyes et al., 2009). Multiple applied pesticides were less influenced than single ones (Zhang, Zhang, Liu, & Hong, 2006) and fluxes linked with the application season of pesticides, were higher in wetter years (Goel et al., 2005).

2.4.1.2. Runoff and drift. Runoff and drift are the most important transfer pathways of pesticides to other sites or surface waters (Johnson et al., 1995; Keikotlhaile, 2011; Otieno et al., 2013). Pesticide emission and damage by droplet spray drift are defined as the amount of pesticide that is deflected out of the treated area by the action of air currents (De Schampheleire, Spanoghe, Brusselman, & Sonck, 2007). Farmers can check wind speed and independent of climate change they can apply pesticides at the desired wind speed conditions reducing drift occurrence. Managing run-off under climate change, is more difficult. The parcel's slope, soil type, texture and structure combined with crop growth and row directionality strongly influence the runoff rate (Steurbaut, 2009).

Precipitation is the main driving factor for agricultural runoff and soil erosion (Cryer, Rolston, & Havens, 1998; Ficklin, Luo, Luedeling, Gatzke, & Zhang, 2010; Johnson et al., 1995; Otieno et al., 2013; Steurbaut, 2009). Runoff of chemicals can vary from 5 to 15% of rainfall

(Wauchope, Johnson, & Sumner, 2004) and is generally caused by localized rainfall and surface runoff from nearby fields or canopy throughfall at urban sites (Donald et al., 2007; Fernandez-Gomez et al., 2013; Roy, Krapac, Chou, & Simmons, 2001; Vryzas, Vassiliou, Alexoudis, & Papadopoulou-Mourkidou, 2009; Zhang, Ye, Hu, Ou, & Wang, 2010). Several studies indicate that increased precipitation enhances runoff contaminated with pesticides (Carere, Miniero, & Cicero, 2011; Oliver et al., 2012; Probst et al., 2005; Reilly et al., 2003; Turner et al., 1994). The numbers and concentrations of pesticides, have already been proven to rise spectacularly, sometimes resulting in a subsequent release into shallow groundwater (Donald, Syrgiannis, Hunter, & Weiss, 1999; Johnson et al., 1995; Noyes et al., 2009; Otieno et al., 2013; Roy et al., 2001). Herbicide fluxes were studied separately and were shown to be (Paetzold, Klein, & Bruemmer, 2007) or not to be (Goel et al., 2005) influenced by precipitation volumes. This ambiguity also occurred in a study considering mancozeb, which showed runoff unrelated to the amount of rain and folpet, which underwent a volume effect (Cabras et al., 2001). In two studies considering herbicides, the effect of precipitation frequency and timing during the planting season was demonstrated (Goel et al., 2005; Paetzold et al., 2007).

Paetzold et al. (2007) reported a positive correlation with the soil moisture level. A spatial and temporal distribution of pesticide residues in surface waters, can thus be expected (Vryzas et al., 2009).

Effects of higher temperatures were also shown by Carere et al. (2011), who revealed an altered distribution and partitioning of contaminants in water and by Ficklin et al. (2010), who demonstrated a decreasing agricultural runoff load. The latter also proved an effect of increasing CO_2 levels on several active ingredients, although found that correlations were contradictive.

2.4.1.3. Leaching. Leaching is the downward movement of a chemical through the soil, eventually reaching the groundwater (Keikotlhaile, 2011). Blenkinsop, Fowler, Dubus, Nolan, and Hollis (2008) and Nolan et al. (2008) concluded that the transfer of pesticides to depth via leaching and to surface water via drainage was mostly influenced by interactions between climate and soil–pesticide combinations. Several studies reported an enhancing effect of precipitation volumes (Bloomfield et al., 2006; Roy et al., 2001; Woodruff et al., 2009) of variable duration (Bloomfield et al., 2006; Nolan et al., 2008), rainfall seasonality (Bloomfield et al., 2006; Loewy, Carvajal, Novelli, & Pechen de D'Angelo, 2006), intensity (Bloomfield et al., 2006) and timing in relation with pesticide application (Lewan, Kreuger, & Jarvis, 2009).

Temperature affects soil mineralogy and geochemistry (Woodruff et al., 2009) and is consequently a main driver for leaching (Bloomfield et al., 2006). In general, research describes a negative correlation with leaching (Beulke, Brown, Fryer, & van Beinum, 2004; Bloomfield et al., 2006; Nolan et al., 2008), often caused by desorption (Stenrod et al., 2008). Temperature not only causes a seasonal effect on pesticide transport in leaching (Nolan et al., 2008), but also reduces the influence of winter rainfall (Blenkinsop et al., 2008). This winter rain exhibits an overall strong influence on the more retained and less degraded residues of spring or autumn applications (Blenkinsop et al., 2008; Bloomfield et al., 2006; Nolan et al., 2008).

2.4.2. Pesticide degradation

Pesticide dissipation is not only influenced by pesticide transport but also degradation. Degradation of pesticides in the soil or atmosphere is realized by phototransformation, chemical or microbial breakdown while, degradation on plant surfaces is caused by photodegradation, evaporation, rainfall wash off and growth dilution (Zongmao & Haibin, 1997) (Fig. 2).

Global warming is acknowledged to accelerate the degradation of chemical components due to accelerated microbial and chemical reaction rates and may reduce concentrations of pesticides in the environment (Ahmad, James, Rahman, & Holland, 2003; Athanasopoulos, Kyriakidis, & Stavropoulos, 2004; Beulke et al., 2004; Bloomfield et al., 2006; Borgå, Saloranta, & Ruus, 2010; Caceres, Megharaj, & Naidu, 2008; Ismail & Azlizan, 2002; Kookana et al., 2010; Noyes et al., 2009; Singh, Singh, Dureja, & Sethunathan, 2003; Stenrod et al., 2008; Wang, Huang, Chen, & Yen, 2009). However, exceptions were discovered in alkaline soils (Caceres et al., 2008) and also in the case of 2,4-D, which degraded faster at 20 °C than 40 °C (Shymko, Farenhorst, & Zvomuya, 2011).

Elevated soil moisture contents and increased precipitation, also enhance pesticide degradation and accordingly persistence (Bailey, 2003; Ismail & Azlizan, 2002; Noegrohati, Narsito, Hadi, & Sanjayadi, 2008; Noyes et al., 2009).

Furthermore, a higher relative humidity was proven to induce a faster environmental pesticide degradation, even though the more difficult initial degradation in this case (Athanasopoulos et al., 2004).

2.4.2.1. Phototransformation. Photolysis or phototransformation occurs when a molecule absorbs energy from sunlight resulting in a chemical alteration of that molecule (Rosenzweig et al., 2001). Because of the kinetic characteristics of these reactions, a temperature effect on phototransformation can be expected (Bloomfield et al., 2006; Noyes et al., 2009; Rosenzweig et al., 2001). Nevertheless, a study by Hebert, Hoonhout, and Miller (2000), contradicted this by demonstrating the temperature independence of for example chlorpyrifos. A final effect was shown in a study on triadimefon, where an increased phototransformation rate in water compared to on-leaf residues, was noted (Nag & Dureja, 2003).

2.4.2.2. Microbial and chemical degradation. The presence of soil microorganisms also plays an important role in pesticide dissipation and transformation (Ahmad et al., 2003; Caceres et al., 2008; Ismail & Azlizan, 2002; Singh et al., 2003; Wang, Huang, Chen, & Yen, 2009). Biological and chemical reaction rates tend to rise at increased temperatures, which is also the case for microbial activity (Chang, Chiang, & Yuan, 2007; Ismail & Azlizan, 2002; Kookana et al., 2010; Wang, Huang, Chen, & Yen, 2009). The soil moisture content enhances microbial activity, but in lesser extent than the temperature effect (Bailey, 2003; Ismail & Azlizan, 2002).

2.4.3. Pesticide fate under climate change

A summary of the pesticide fate and more specifically, the influencing factors on the initial deposit, is presented in Fig. 2.

Climate change can reduce concentrations of pesticides due to a combination of increased volatilization and accelerated degradation (Noyes et al., 2009; Zhang et al., 2006), both strongly affected by a high moisture content, elevated temperatures and direct exposure to sunlight (Johnson et al., 1995; Otieno et al., 2013). Those last two elements also influence the chemical alteration of pesticides (Rosenzweig et al., 2001). In general, pesticide dissipation seems to be benefitted by higher amounts of precipitation in addition to temperature, degradation and sorption (Stenrod et al., 2008). Within leaves, the uptake and release equilibrium of semi-volatile pesticides is reached faster at higher temperatures (Bloomfield et al., 2006) and transport through the atmosphere, is predominantly impacted by local surroundings (van Dijk & Guicherit, 1999; Yeo et al., 2003). So, the timing and intensity of rainfall influence pesticide persistence and efficiency (Bailey, 2003; Rosenzweig et al., 2001). In addition, temperature and light affect pesticide persistence through chemical alteration. This results in an effect on the pesticides used to control and/or prevent pest outbreaks (Rosenzweig et al., 2001). In general, a warmer climate may necessitate an increased pesticide usage (Noyes et al., 2009; Rosenzweig et al., 2001). Even though the lifetime of some products might be increased (Jager, Bourbon, & Levsen, 1998), a reduced period of effect results in more applications needed to sufficiently protect crops.

2.4.4. Pesticide ecotoxicity

Ecotoxicity can be influenced by many processes shown in Fig. 2. For example, adsorption and the formation of non-extractable residues, can be seen as a decrease in bioavailability or toxicity of pesticides, resulting in a higher need for pesticide inputs (Barriuso, Benoit, & Dubus, 2008).

In general, a positive correlation between increased temperatures and ecotoxicity is reported (Noyes et al., 2009; Seeland et al., 2012), except for pyrethroids and DDT which are thought to be more toxic under low temperature conditions (Noyes et al., 2009). The temperature effect on pesticide ecotoxicity can be clarified by a changing toxicokinetic profile, resulting in an altered absorption and substance elimination (Seeland et al., 2012). Studies on *Chironomus riparius*, *Palaemonetes pugio* and *Mya arenaria* demonstrated this increased acute toxicity of applied pesticides at higher temperatures (Delorenzo et al., 2009; Greco et al., 2011; Seeland et al., 2012). For *Physella acuta*, a complex pesticide–temperature interaction with a life stage specific and temperature dependent ecotoxicity was discovered. Finally, a combined effect of fungicide exposure and thermal stress was proven to increase the average mortality of *Daphnia magna* (Seeland et al., 2012).

Indirectly, increasing temperatures can alter the ability of species to respond to pesticide exposures or alter pesticide uptake and metabolism, thus assumedly increasing pesticide bio-efficacy (Greco et al., 2011; Patterson et al., 1999).

2.4.5. Pesticide application

During pesticide application, a large amount of spraying liquid ends up on the soil, depending on drop size, crop density and maturity. In the case of increasing precipitation, rain-fastness will be an important characteristic. The link with extreme events, additionally influences the timing of pesticide applications (Johnson et al., 1995; Otieno et al., 2013). For example, predicted higher soil moisture deficits in autumn can limit field work or move it to an earlier date than now, while high soil moisture in humid areas can also hinder field operations (Chen & McCarl, 2001; Miraglia et al., 2009; Rosenzweig et al., 2001). This can oblige farmers to apply autumn herbicide treatments earlier resulting in a more difficult winter weed control (Bailey, 2003).

3. Conclusion

Several elements that can influence pesticide use, have been presented. In the first instance, pesticide producing companies will strive to supply optimal products. (New) pesticide active ingredients will have to be formulated in rain-fast products for agricultural use. For farmers, the season and timing of the pesticide application, seasonal precipitation and temperature in relation to environmental factors, will strongly influence management decisions (Nolan et al., 2008; Reilly et al., 2003).

Secondly, climate change affects crop characteristics and appearance due to a lengthening active growing season (Myneni, Keeling, Tucker, Asrar, & Nemani, 1997). Corresponding advances in phenology are to be expected (Fontaine et al., 2009; Lepetz et al., 2009), while climatic variation can alter plant resistance for pests but also for pesticides (Harvell et al., 2002). According to Reilly et al. (2003), overall climate change will be beneficial to crop productivity, despite the risks at regional levels. Local climates, will strongly determine which areas are (still) suitable for a crop to be cultivated (Jackson et al., 2011; Myneni et al., 1997).

Third, the key factor for pesticide use is the presence and severity of weeds, pests and diseases in a crop. These organisms are affected by climate change in a similar way as the crops. There is also a high likelihood of genetic adaptation (Bloomfield et al., 2006; Lepetz et al., 2009), although the first response will probably be a phenology alteration or geographical redistribution (Scherm, 2004). Pest and disease invasions are aided by mostly temperature effects. Finally, pesticide efficiency, represented by the initial deposit, pesticide fate and (eco-) toxicity, also has a major impact on pesticide use.

In general, pesticide losses of mobile active substances are mainly influenced by the time gap between extreme weather events and pesticide application (Blenkinsop et al., 2008; Nolan et al., 2008). In soil, transport of pesticides is thus mainly driven by rainfall seasonality, intensity and temperature increases but also land-use changes which indicates an indirect impact on the long term impact (Bloomfield et al., 2006). The soil-biological microbial activity is affected by moisture content and soil temperature (Barriuso et al., 2008).

Even though some reducing effects, increasing temperatures overall will result in higher volumes of pesticides that will have to be applied more often. An increased intensity of pesticide use is expected in the form of higher amounts, doses, frequencies and different varieties or types of applied products (Bloomfield et al., 2006; Goel et al., 2005; Hall et al., 2002; Miraglia et al., 2009; Noyes et al., 2009; Rosenzweig et al., 2001). An adapted pesticide use will finally impact consumer exposure at the end of the food chain.

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