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Impacts of sublethal insecticide exposure on insects — Facts and knowledge gaps

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Abstract

The biodiversity and biomass of insects is dramatically declining due to various anthropogenic factors. One of these factors is the use of insecticides to protect plants from pests. However, apart from the targeted pest insects, thousands of non-target organisms face traces of insecticides that are not lethal but can affect numerous traits of the individual, including development, physiology, behaviour and communication. In the present review, key facts on impacts of sublethal insecticide exposure on such traits are summarised. Attributable to various abiotic and biotic processes, insecticide concentrations may become sublethal in space and time. Nevertheless, these concentrations impede insect development, reducing growth and survival, but sometimes also enhance reproductive performance. The effects are species-specific, but sensitivity also differs within species depending on the developmental stage, sex and population. Furthermore, insecticide exposure influences several immunity pathways and causes changes in behaviour. Such changes are mostly studied on the level of behavioural traits. However, also effects on the consistency of overall individual behavioural phenotypes, i.e. personalities, should be investigated, which have consequences on individual fitness and on the effectiveness of biocontrol agents. Moreover, insecticides can act as info-disruptors, impeding signal production and perception during chemical communication at various levels. Finally, microbial symbionts may modify insect responses to insecticides, being of particular interest for biotechnological approaches. Here, methodological issues are discussed and knowledge gaps and potential future research directions are highlighted. Understanding the mechanisms of dose-dependent insecticide impacts on organisms and their cascading effects on higher levels of biological organisation and on subsequent generations are of utmost importance for proper insecticide use.

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Introduction

Insects play important roles in ecosystems as members of food chains and by providing ecosystem services, such as pollination and natural pest control. For example, 60% of the birds depend on insects as a food source, while about 80% of wild plants rely on insect pollinators (Hallmann, Quadt-Hallmann, & von Tiedemann 2007). A recent study performed in protected areas in Germany demonstrated that the aerial insect biomass has decreased by more than 75% within the last quarter of a century (Hallmann et al. 2017). The decline is likely worse in non-protected areas, in particular in land used for conventional agriculture, where insecticides are applied (Rader, Bartomeus, Tylianakis, & Laliberte 2014; Uchida, Hiraiwa, & Ushimaru 2016). Worldwide around 590,000 t of insecticides are applied per year (De, Bose, Kumar, & Mozumdar 2014). Because the worldwide human population is expected to rise within the next 33 years from 7.6 to 9.8 billion (United Nations 2017), the demand for agriculturally-used land is growing (Schmitz et al. 2014) and with this an increase in insecticide application in terms of both application times and total amounts, and thus increased agrochemical pollution, are expected (Guedes, Smagghe, Stark, & Desneux 2016). The short- and long-term consequences of this insecticide use for insect life-history traits are far from being fully understood.

Insecticides have various modes of action, targeting different primary target sites in the insect's physiology (Fig. 1). In conventional agricultural crop cultivation but also for many hobby gardeners the aim is to kill insect pests. One of the largest dilemmas in applying insecticides is the fact that these chemicals do not only kill or at least affect the targeted pests, but that also numerous non-target insect species come into contact with lethal or sublethal insecticide doses in the treated areas and the surroundings (Guedes et al. 2016). These different concentrations can rapidly lead to selection of resistance in pest insects (van Toor et al. 2008; Casida & Durkin 2013) and, moreover, alter community structure

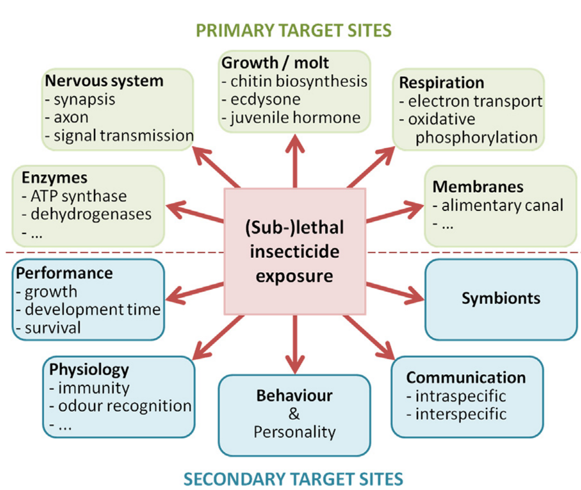

Fig. 1. Key primary and secondary target sites of insecticides.

(Guedes, Walse, & Throne 2017). Furthermore, the insecticide traces do not only impact the insects' physiology but also their behaviour and communication (Fig. 1; Xavier et al. 2015; Navarro-Roldán & Gemeno 2017; Tappert, Pokorny, Hofferberth, & Ruther 2017). Apart from pronounced influences on the directly exposed individuals (short-term) they may additionally impact subsequent generations (long-term) (Guo et al. 2013; Costa et al. 2014; Müller, Prosche, & Müller 2017). Potentiated throughout food webs, such effects have far-reaching consequences on species interactions, population dynamics and entire ecosystems (Brittain & Potts 2011; Guedes et al. 2016).

In a comprehensive review written almost a decade ago, Desneux, Decourtye, and Delpuech (2007) summarised the sublethal effects of insecticides on beneficial arthropods. This review mainly focused on pollinators, in particular honey bees, and natural enemies. However, many other herbivores are affected by insecticides that are neither pests nor obvious beneficials. In the present paper, selected novel findings on effects of sublethal insecticide concentrations on various life-history and demographic traits of different insect species are highlighted. In the beginning, I argue that the differentiation between lethal *versus* non-lethal insecticide concentrations or between target and non-target organisms is not always clear-cut. Furthermore, I shortly list primary target sites and then introduce various secondary target sites that are potentially affected by insecticides (Fig. 1), with a particular emphasis on chemical communication. Finally, potential positive effects of very low insecticide concentrations on insects as well as rather detrimental long-term, transgenerational effects are presented. In each section, methodological considerations, knowledge gaps and areas of further research are pointed out.

Concentrations

A fundamental goal of insecticide pest control is to determine the optimal quantity that is needed to effectively reduce damage of crop plants by pests but at the same time minimise impacts on the environment (Guedes et al. 2016; Navarro-Roldán, Avilla, Bosch, Valls, & Gemeno 2017). However, many insecticides are sprayed on crop plants and thereby enter the atmosphere *via* drift. Moreover, the chemicals, including the active ingredient compounds and the formulation aggregates, degrade over time in plants, animals, soil and water. Thus, various abiotic and biotic processes change the insecticide concentrations at a spatial and temporal scale (Lalouette et al. 2016). As a consequence, lethal and sublethal insecticide concentrations exist in numerous environmental compartments. A sublethal concentration is defined as inducing no apparent mortality in the experimental population, but potentially causing physiological or behavioural effects on individuals that survive the insecticide exposure (Desneux et al. 2007). However, low doses of insecticides that are not lethal can in a few cases also lead to an increase in insect reproduction (see Positive effects of insecticides on insects).

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