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1 Pesticide dosing must be guided by  
2 ecological principles

3  
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12

13 **Insecticide use could be reduced if dose recommendations move from a**  
14 **toxicological perspective (how much is needed to kill an insect pest) to an**  
15 **ecological perspective (how much is needed to protect a crop).**

16

17 Insect populations are in sharp decline, with potentially catastrophic consequences for  
18 ecosystem function<sup>1</sup>. This is a complex problem, but the widespread use of pesticides  
19 is certainly part of it<sup>2,3</sup>. Debates continue about whether some insecticides should be  
20 banned, but where bans have happened different insecticides have been substituted.  
21 These may be no less harmful to insects<sup>4</sup>. Agriculture needs to move away from such  
22 a heavy reliance on pesticides and adopt an integrated pest management approach  
23 (IPM)<sup>5</sup> and a better regulatory process<sup>6</sup>, but this change will take time with the IPM  
24 approaches proposed to date. Here we argue that we could immediately reduce the  
25 amounts of insecticide applied to the environment without necessarily risking loss of  
26 crop yields if we rethink pesticide dosing recommendations based on ecological  
27 principles. This action alone will not solve the pesticide problem, but will reduce  
28 pesticide pollution to win time while we transition to a more sustainable agricultural  
29 model.

30

31 Since 1990 the amount (measured in weight) of insecticide applied to farmland in the  
32 UK has actually decreased, but this is because modern insecticides are far more toxic  
33 than older options<sup>7</sup>. For example, neonicotinoids are 10,000 times more toxic to  
34 insects than even DDT<sup>8</sup>! In the UK, the land area treated with insecticides has  
35 increased sharply since 2000, and the frequency and diversity of insecticide  
36 treatments has also increased<sup>9</sup>. Therefore, in recent decades the toxicity of the  
37 environment in the UK to insects has increased.

38 The justifications given by any pesticide supplier for their dose recommendations is  
39 seldom clear. The research performed to justify the dose is proprietary and not in the  
40 public sphere<sup>6</sup>, which is itself a problem. Usually dose guidelines, when given, refer to

41 a measure of the LC50 (the dose lethal to 50%) of the active ingredient(s) of the  
42 pesticide against the target, and pesticides are recommended to be used at doses  
43 causing a fast death in the targeted pests (Table 1). We argue this kind of effect is not  
44 needed to control damage to crops from insect pests.

45

46 Currently insecticides are applied at concentrations in the upper range of the mortality  
47 dose-response curve (Figure 1, dashed lines) to deliver a rapid and total elimination  
48 of the pest. Mortality dose-response relationships are sigmoid<sup>10</sup>. As a consequence, a  
49 dose that yields even 90% mortality of the target organism can be far less than a dose  
50 yielding a promise of 100% mortality. For example, in the case of the cotton whitefly  
51 (*Bemisia tabaci*, Figure 1B), a target of 90% mortality would reduce pesticide amount  
52 used by 75% from the current dose recommendation.

53

#### 54 **Sublethal effects of insecticides can be sufficient to eliminate economic damage** 55 **to crops**

56 Target insect pests may not need to be killed outright to prevent economic crop  
57 damage. Pesticides also have sublethal effects at low doses (Figure 1), which can  
58 affect the feeding, vision, mobility, orientation, learning and fertility of insects<sup>23</sup>. These  
59 sublethal effects are known to severely reduce populations of beneficial insects<sup>24,25</sup>,  
60 but they have been largely overlooked for control of targeted pest insects.

61 There are examples of sublethal effects of commercial insecticides being sufficient to  
62 control target pest insects. Trees can be injected with highly concentrated doses of  
63 neonicotinoids to protect them against insect herbivores. Even when the insecticide  
64 doses injected into the trunks are highly concentrated, only sublethal concentrations  
65 end up in the leaves and twigs<sup>20,26</sup> (see purple dashed line on Figure 1B for levels  
66 found in trees). These sublethal doses have nonetheless been shown to provide  
67 effective control against the Asian longhorn beetle<sup>26</sup> at doses 17 times less than the  
68 100% lethal dose<sup>20</sup>. Two common insecticides, at sublethal doses, were found to  
69 cause the silverleaf whitefly to stop feeding and lay 75% fewer eggs<sup>27</sup>, and tefluthrin

70 inhibits feeding in the corn rootworm at a concentration causing only 20% direct  
71 mortality<sup>28</sup>.

72 It is not necessary to kill all target insects to eliminate a pest population. The IPM  
73 paradigm has argued for decades that it is not necessary to treat a crop when the  
74 density of the pest is too low to cause any significant economic damage<sup>29</sup>. Using  
75 additional principles from ecology<sup>30</sup>, we further argue that for low density pest  
76 populations sublethal insecticide concentrations are likely sufficient to precipitate their  
77 extinction. Stochastic dynamics and Allee effects (the effect of population density on  
78 mean individual fitness) can be sufficient to drive small populations of pests to  
79 extinction<sup>30</sup>. The original description of the Allee effect came from a pest management  
80 study. Allee<sup>30</sup> reported that tsetse fly baits did not need to catch 100% of the flies to  
81 drive a local population to extinction. Allee effects in low density populations can be  
82 due to reduced foraging efficiency, mate finding, reduced predator dilution, or from  
83 inbreeding<sup>31</sup>. Sublethal effects of pesticides can exacerbate these effects if they  
84 damage the capacity of insects to find food, mates or to avoid predators<sup>31</sup>.

85 Insects are likely exposed to mixtures of pesticides<sup>3</sup>. Insecticide residues that  
86 accumulate in the environment, and other pesticides such as fungicides can have  
87 additive or synergistic effects, including on beneficial insects<sup>3</sup>. Interactions between  
88 pesticides influence how much need be applied to control a pest. Fungicidal  
89 treatments are well-known for their negative effects on invertebrates<sup>3,32</sup>. For example,  
90 two of the most common fungicides affect the development of Colorado potato beetle  
91 larvae, and can increase the susceptibility of the pest to imidacloprid<sup>33</sup>. If interactions  
92 between pesticides are better understood, it may be possible to reduce the amounts

93 of pesticide used even further by applying principles from community ecology to  
94 pesticide application<sup>34</sup>.

95

96 **What pesticide dose is needed to prevent economic damage to a crop?**

97 Few pesticides dosage guidelines are given in terms of economic outcomes for the  
98 crop, or assurance of yield. Most studies of insecticide dosing solely focus on lethality  
99 to the target insect rather than the economic benefits of the treatments (and lethality  
100 is widely used as a marketing argument, see Table 1). In fact, demonstrating economic  
101 benefits from insecticide treatments is not straightforward<sup>2</sup>. In the UK, no clear gains  
102 in crop yields have been seen linked to increased neonicotinoid use<sup>2</sup> perhaps because  
103 neonicotinoids are often applied prophylactically where no pest are present or  
104 because their effects on beneficial insects may negatively affect yields<sup>2</sup>. If we are not  
105 seeing benefits from high doses of insecticides, we have an even greater imperative  
106 to rethink insecticide doses.

107 Applying insecticides at the minimum dose needed to reduce the target pests' fitness  
108 to zero will also help manage insecticide resistance. This echoes lessons learned from  
109 managing antibiotic resistance: manage resistance by tightly controlling and  
110 minimising antibiotic use<sup>35</sup>. By contrast, widespread prophylactic use of long-lived  
111 pesticides at high doses is alarmingly common<sup>2</sup> which may explain why insecticide  
112 resistance keeps increasing globally<sup>2,36</sup>.

113 Controlling pest resistance on the long-term will only be achieved by an IPM  
114 approach<sup>36</sup>. This should involve multiple IPM strategies, such as crop rotation, the use  
115 of short lived pesticides and alternating pesticide treatments with different modes of

116 actions<sup>36</sup>. Reducing the dose of pesticide will additionally slow the development of  
117 resistance in populations by reducing the extent and intensity of the selection pressure  
118 for insecticide resistance.

119

## 120 **Rethinking necessary insecticide doses**

121 Arguing to end-users that total eradication of pests is not needed to assure their  
122 economic returns will require changing expectations. It will take some serious re-  
123 education to reassure growers that a low pesticide dose that may leave some pests  
124 visible in a crop has worked to protect the crop. There is also work to be done to assure  
125 growers that a lower dose will be sufficient to protect their livelihoods. But a benefit to  
126 farmers will be that a lower insecticide dose will be cheaper to apply and cause less  
127 damage to beneficial insects such as pollinators.

128 We do not pretend that this will solve the problem of declining insect populations.  
129 Reducing insecticide dosing will not eliminate insecticide residues, but it will reduce  
130 the severity and the scale of the problem. This could be done now with no cost to crop  
131 yields. It may be a short-term, temporary and partial patch across a far larger and more  
132 complex problem, but perhaps this patch can help us win time to change pesticide  
133 regulatory processes, shift to an IPM culture, and globally redesign the model of food  
134 production into a more sustainable form.

135

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139

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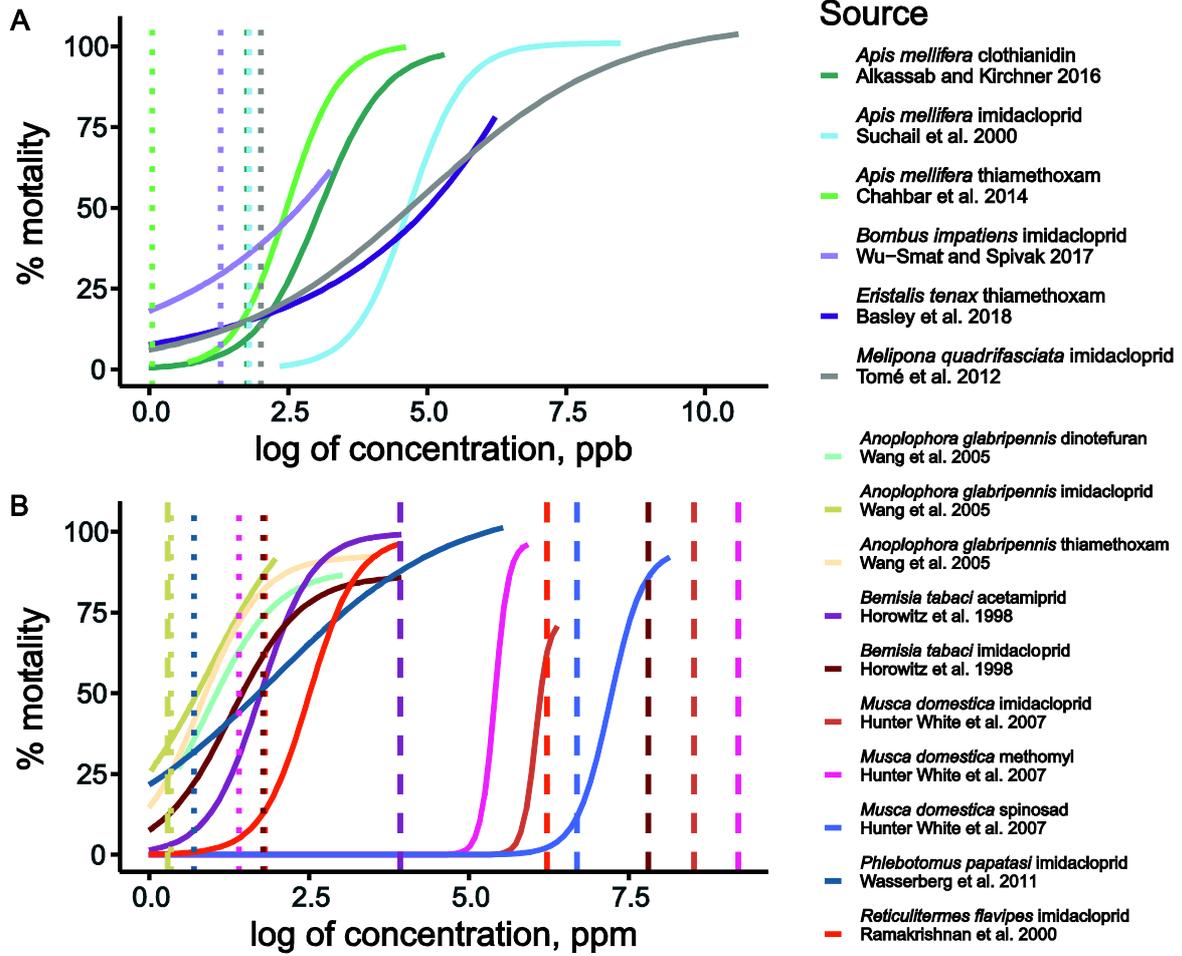
234

235 **Figure legend**

236

237 **Figure 1:** Examples of dose-response mortality curves for non-target (A) and target  
238 (B) insects<sup>11-21</sup>. Concentration is shown on a log scale. Colours represent different  
239 insect-insecticide combinations. Sublethal effects with impact on fitness (dotted lines)  
240 are often detected at doses well below the concentrations killing 50% or 100% of the  
241 population. Recommended doses for target insects (dashed lines, see supplementary  
242 methods) often exceed concentrations known to cause 100% mortality. Non-target  
243 insects are often more sensitive than targeted pests to insecticides<sup>22</sup>, so  
244 concentrations are shown in parts per billion for non-target (A) and parts per million  
245 for target insects (B).

246



247

248

249

250 Table 1: Research performed to justify the dose is mostly proprietary, but usage  
 251 guidelines for popular insecticides promise rapid eradication of pests (see  
 252 supplementary methods for references).

<b>Manufacturer</b>	<b>Pesticide</b>	<b>Group</b>	<b>Marketed effect on pest</b>
BASF	Dinotefuran	neonicotinoid	"control pyrethroid-resistant pests quickly"
Bayer	Spirotetramat	keto-enol	"suppression of woolly apple aphids", figure shows 80-100 "% control"
Bayer	Thiacloprid	neonicotinoid	"suppression of woolly apple aphids", figure shows 100% mortality
Corteva	Spinetoram and methoxyfenozide	spinosyn, diacylhydrazine	"faster knockdown and consistent control"
Corteva	Spinetoram and sulfoxaflor	spinosyn, sulfoximine	"for control or suppression of listed pests"
Corteva	Chlorpyrifos and Lambda-cyhalothrin	organophosphate, pyrethroid	"fast knockdown and excellent residual control of a broad spectrum of insects"
Syngenta	Emamectin	avermectin	Figures show 90 "% control" of a moth, and 100% bee mortality three hours after application
Syngenta	Pymetrozine	pyridine	"excellent control of aphid and suppression of whitefly populations"
Syngenta	Thiamethoxam	neonicotinoid	"death occurs by starvation within 24 hours"
Syngenta	Chlorantraniliprole and Abamectin	ryanoid, avermectin	"feeding stops within minutes, larvae start to wriggle then become paralysed, death follows after 48 hours"

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254