Justification of parameter ranges.

In the following section we provide a justification of the parameter ranges used in the global analysis. The global analysis is intended to be able to randomly generate insect populations with parameters that are representative of agricultural foliar insect pests. As such the list below is far from exhaustive, but instead gives an indication of the ranges of values that have been found in the literature.

# Life-history parameters

## Reproduction

The life-history of various insect pests can differ dramatically. While many insect pests undergo sexual reproduction, such as *Bemisia tabacii* (Li et al., 1989) and *Meligethes aeneus* (Williams and Free, 1978), some, particularly within the Aphidoidea, can reproduce asexually through parthenogenesis (Blackman, 1974).

### Ploidy

While most agricultural insect pests such as aphids and weevils are diploid, there are several significant haplodiploid insect pests such as *Bemisia tabaci* (Denholm et al., 1998) and *Frankliniella occidentalis* (Jensen, 2000), as well as functionally haplodiploid insects such as the coffee berry borer (Brun et al., 1995).

### Life cycle

Most arthropods are holometabolous (that is they have a complete life cycle incorporating four stages: egg, larvae, pupa and adult stages), however several insects including aphids are hemimetabolous, omitting the egg and pupal stages (Kollmann et al., 2011).

Similarly, many insect pests are multivoltine (producing many generations within a year), while others such as *Meligethes aeneus* are univoltine (only having one generation per year) (Hopkins and Ekbom, 1996).

## Birth rate (per female per day)

The fecundity of insects varies over their lifespan (Sauvion et al., 1996). In the model we use a constant birth rate, however, and therefore divide the total number of eggs produced through an adult’s lifespan by the reproductive period. The fecundity of insects is highly dependent on both temperature (Wang and Tsai, 1996) as well as other environmental factors such as host suitability (Hopkins and Ekbom, 1999). There is therefore a large range of potential birth rates of insect pests in practical situations.

|  |  |  |  |
| --- | --- | --- | --- |
| **Insect** | **Host** | **Value** | **Reference** |
| *Meligethes aeneus* | Oilseed rape | 1.4/female /day | Ekbom and Ferdinand (2003) |
| *Diuraphis noxia* | Wheat | 1.2-2.0/adult/day | Aalbersberg et al. (1987) |
| *Myzus persicae* | Artificial diet | 1/adult/day | Sauvion et al. (1996) |
| *Bemisia argentifolii* | Aubergine | 2.2-7.3/female/day | Wang and Tsai (1996) |
| *Aphis glycines* | Soybean | 6/female/day | Mccornack et al. (2004) |
| *Sitona lineatus* | Field pea | 18/female/day | CáRcamo et al. (2012) |
| *Plutella xylostella* | Radish | 23/female/day | Cao and Han (2006) |

Range: 1.0-20.0 per female per day (or 0.5-10 per adult per day for clonal insects).

## Lifespan of insect stages (days)

The lifespan of insect stages is also temperature-dependent (De Conti et al., 2010), and therefore highly variable in field conditions. The following longevities represent a variety of insects in different conditions. The longevity of diapausing insect stages is not considered.

|  |  |  |  |
| --- | --- | --- | --- |
| **Insect** | **Stage** | **Value** | **Reference** |
| *Meligethes aeneus* | Egg | 2-12 days | Nielsen and Axelsen (1988) |
| *Bemisia argentifolii* | Egg | 3.8-19.4 days | Yang and Chi (2006) |
| *Ceratothripoides claratris* | Egg | 2.5-5 days | Premachandra et al. (2004) |
| *Bemisia argentifolii* | Nymph | 12-56 days | Yang and Chi (2006) |
| *Diuraphis noxia* | Nymph | 10 days | Aalbersberg et al. (1987) |
| *Rhopalosiphum padi* | Nymph | 6 days | Li et al. (2018) |
| *Ceratothripoides claratris* | Larvae | 3-7 days | Premachandra et al. (2004) |
| *Ceratothripoides claratris* | Pre-pupa and pupa | 2.5-5 days | Premachandra et al. (2004) |
| *Meligethes aeneus* | Pupa | 10-18 days | Nielsen and Axelsen (1988) |
| *Macrospohium euphorbiae* | Adult | 10-20 days | De Conti et al. (2010) |
| *Meligethes aeneus* | Adult | 60 days | Hopkins and Ekbom (1996) |
| *Bemisia artentifolii* | Adult | 5.5-15.8 days | Yang and Chi (2006) |
| *Rhopalosiphum padi* | Adult | 14.5 days | Li et al. (2018) |
| *Diuraphis noxia* | Adult | 35-56 days | Aalbersberg et al. (1987) |

Range: 2-60 days for each insect stage.

## Mortality of insect stages (per capita per day)

Non-lifespan dependent mortality of insects is highly variable, affected as it is by insect density, the environment, and natural predators (Büchi, 2002). The following references give mortalities typically for a different stage or multiple stages. Estimates of adult natural mortality were not found (presumably as it is difficult to separate age-dependent mortality from other forms of mortality), and so similar estimates were used for the adults as for other stages.

|  |  |  |  |
| --- | --- | --- | --- |
| **Insect** | **Stage** | **Mortality** | **Reference** |
| *Plutella xylostella* | Egg | 13% | Cao and Han (2006) |
| *Plutella xylostella* | Larva | 19% | Cao and Han (2006) |
| *Tialeurodes vaporariorum* | Pre-adult | 10-90% | van Lenteren and Noldus (1990) |
| *Rhopalosiphum padi* | Pre-adult | 83% | Li et al. (2018) |
| *Meligethes aeneus* | Larvae and pupae | 66-96% | Büchi (2002) |
| *Meligethes aeneus* | Larvae | 62% | Cook et al. (2004) |
| *Plutella xylostella* | Pupa | 7% | Cao and Han (2006) |
| *Meligethes aeneus* | Pupa | 19% | Cook et al. (2004) |

Range: 5%-90% for each stage.

## Intrinsic rate of increase

The intrinsic rate of increase of insects gives an estimate of the overall growth rate of an insect population and is a frequently calculated – and therefore findable - metric.

|  |  |  |  |
| --- | --- | --- | --- |
| **Insect** | **Host** | **r** | **Reference** |
| *Myzus persicae* | Chrysanthemum | 0.16-0.17 | Vehrs et al. (1992) |
| *Myzus persicae* | Cereals | 0.04-0.26 | Davis and Radcliffe (2008) |
| *Aphis gossypii* | Cotton | 0.17-0.41 | Kersting et al. (1999) |
| *Tetranychus urticae* | Strawberry | 0.39 | Cédola et al. (2013) |
| *Chaetosiphon fragaefolii* | Strawberry | 0.19 | Cédola et al. (2013) |
| *Rhopalosiphum padi* | Wheat | 0.32 | Li et al. (2018) |
| *Aphis glycines* | Soybean | 0.03-0.15 | Myers and Gratton (2006) |
| Various | Various | 0.03-0.57 | Trumper and Holt (1998) |

Range: 0.05-0.5.

## Carrying capacity

Many insect pests exhibit density-dependent population growth, and as such we have used a logistic population growth equation to model the insect dynamics within each field. Estimates of the carrying capacity – the maximum possible density of insects – depend on the scale in question; in our article we use a single plant as our unit area. Here we report maximum estimates reported or derived from population growth curves.

|  |  |  |  |
| --- | --- | --- | --- |
| **Insect** | **Host** | **Maximum number per plant** | **Reference** |
| *Myzus persicae* | Brussel sprout | 4000 | Van Emden and Harrington (2007), pg 551 |
| *Myzus persicae* | Oilseed rape | 600 | Desneux et al. (2005) |
| *Myzus persicae* | Chrysanthemum | 200 | Vehrs et al. (1992) |
| *Aphyis glycines* | Soybean | 50 | Myers and Gratton (2006) |
| *Meligethes aeneus* | Oilseed rape | 14 | Mauchline et al. (2017) |

Range used: 10-10000 insects per plant.

## Emergence rate

The rate at which insect pests enter the agricultural crop is variable (M J Tauber and Tauber, 1976). The emergence period of several insects pests can be found in the literature, being the time over which insects emerge from their overwintering populations. To estimate a daily emergence rate from this, the emergence rate was estimated by estimating the rate until half the insects had emerged. That is , where is half the emergence period. An emergence range of 0.02-0.1 insects per day was chosen, corresponding to 50% of the population having emerged between 7 – 35 days after the start of the simulation.

|  |  |  |  |
| --- | --- | --- | --- |
| **Insect** | **Emergence period** | **Estimated emergence rate** | **Reference** |
| *Meligethes aeneus* | 60 days | 0.023 | Rusch et al. (2012) |
| *Cydia nigricana* | 42 days | 0.033 | Graham (1985) |

Range: 0.02 – 0.1 per day.

# Movement parameters

## External untreated population size

The size of the external untreated population depends primarily on how polyphagous the agricultural insect pest is. If the insect feeds solely on the crop in question, such as (at least locally) *Heliothis virescens* (Andow, 1983), the relative size of the untreated external population will be small, whereas if the insect is highly polyphagous, particularly of non-agricultural crops, as with *Myzus persicae* (Weber, 1985), then the untreated population will be large.

Range: 0-10 fold.

## Movement to untreated population

The rate of movement to untreated populations outside the treated crop depends on the motility of the adult insect stages. Although figures are again hard to estimate, it is clear that there is a high level of gene flow between pollen beetle populations (Kazachkova et al., 2007), suggesting a high rate of movement. Additionally 1/3 of adult western corn rootworms have been found to leave their natal maize field within the course of a season (Levay et al., 2014). We assume that up to 2% of the adult population may leave the field per day.

Range: 0-0.02 per day.

## Proportion of crop within crop refuge

Heterogeneity of crop spray occurs due to interception of insecticide by leaves near the top of the canopy resulting in lower pesticide coverage at lower levels (C. Derksen et al., 2008; E. Wolf and P. Daggupati, 2009), and from spray heterogeneity resulting from spray deposition (Nansen et al., 2015). We simplify this by assuming there is a proportion of the crop that receives no insecticide. The amount of a crop plant that receives very little pesticide can vary up to as much as one third of the crop in soybean, where the pesticide coverage is as little as 0.2-10% of the leaf area (E. Wolf and P. Daggupati, 2009).

Range: 0-33% of the crop.

## Movement rate between treated crop and untreated refuge

The movement of larval / adult stages of insect pests within the canopy can vary considerably depending on the motility of the insect stages. In a study of the movement of aphids, they found that all initial 10 apterous aphids had moved from their initial radish plant to other plants within three days (Hodgson, 1991). Clearly the movement rate between the treated and untreated areas depends on the spatial distribution. We assume a rate of 0.1-2.0, such that an insect may move between the populations on average every 10 days or every half a day.

Range: 0.1 – 2.0 per day.

# Insecticide parameters

## LC50 of susceptible strains

The following table presents a sample of LC50s from susceptible strains of several well-known insect pest species. In the article the LC50 value of the susceptible strain is not set randomly, so these are only relevant in that they are the compliment of the gradients of the dose-mortality relationship.

|  |  |  |  |
| --- | --- | --- | --- |
| **Insect** | **LC50** | **Insecticide** | **Reference** |
| *Myzus persicae* | 0.271 | Cyantraniliprole | Foster et al. (2012) |
| *Aphis glosyphii* | 0.173 | Cyantraniliprole | Foster et al. (2012) |
| *Myzus persicae* | 0.46 | Imidacloprid | Foster et al. (2003) |
| *Myzus persicae* | 0.35 | Acetamiprid | Foster et al. (2003) |
| *Myzus persicae* | 2.12 | Nitenpyram | Foster et al. (2003) |
| *Bemisia tabaci* | 0.043 | Pyriproxyfen | Horowitz et al. (2005) |
| *Bemisia tabaci* | 3.6 | Cypermethrin | Cahill et al. (1995) |
| *Bemisia tabaci* | 0.34 | Bifenthrin | Cahill et al. (1995) |
| *Bemisia tabaci* | 1.3 | Etofenprox | Cahill et al. (1995) |
| *Bemisia tabaci* | 14 | Monocrotophos | Cahill et al. (1995) |
| *Bemisia tabaci* | 6.1 | Profenofos | Cahill et al. (1995) |
| *Bemisia tabaci* | 2.9 | Chlorpyrifos | Cahill et al. (1995) |
| *Meligethes aeneus* | 2.8 | α-cypermethrin | Philippou et al. (2011) |
| *Plutella xylostella* | 0.048 | Chlorantraniliprole | Troczka et al. (2012) |
| *Plutella xylostella* | 0.15 | Chlorantraniliprole | Troczka et al. (2012) |

Range: 0.

## Gradient logit-dose lines of susceptible insect strains

The following table gives the slope of the LC50 given above against susceptible strains of insects.

|  |  |  |  |
| --- | --- | --- | --- |
| **Insect** | **Slope** | **Insecticide** | **Reference** |
| *Myzus persicae* | 1.6 | Cyantraniliprole | Foster et al. (2012) |
| *Aphis glosyphii* | 1.2 | Cyantraniliprole | Foster et al. (2012) |
| *Myzus persicae* | 3.4 | Imidacloprid | Foster et al. (2003) |
| *Myzus persicae* | 2.0 | Acetamiprid | Foster et al. (2003) |
| *Myzus persicae* | 1.2 | Nitenpyram | Foster et al. (2003) |
| *Bemisia tabaci* | 1.4 | Pyriproxyfen | Horowitz et al. (2005) |
| *Bemisia tabaci* | 1.6 | Cypermethrin | Cahill et al. (1995) |
| *Bemisia tabaci* | 2.0 | Bifenthrin | Cahill et al. (1995) |
| *Bemisia tabaci* | 2.2 | Etofenprox | Cahill et al. (1995) |
| *Bemisia tabaci* | 2.6 | Monocrotophos | Cahill et al. (1995) |
| *Bemisia tabaci* | 4.9 | Profenofos | Cahill et al. (1995) |
| *Bemisia tabaci* | 3.3 | Chlorpyrifos | Cahill et al. (1995) |
| *Meligethes aeneus* | 1.6 | α-cypermethrin | Philippou et al. (2011) |
| *Plutella xylostella* | 1.3 | Chlorantraniliprole | Troczka et al. (2012) |
| *Plutella xylostella* | 3.8 | Chlorantraniliprole | Troczka et al. (2012) |

Range: 0.5 – 6.0

## Decay rate of each insecticide

The decay rate of an insecticide is related to the half-life of an insecticide, as , where is the half-life and is the decay rate.

|  |  |  |  |
| --- | --- | --- | --- |
| **Insecticide** | **Half-life (days)** | **Estimated decay rate** | **Reference** |
| Fipronil | 2.6 | 0.26 | Pei et al. (2004) |
| Chlorpyrifos | 5.7 | 0.12 | Veierov et al. (1988) |
| Carbaryl, methomyl, endosulfan | 2-8 | 0.14-0.35 | Walgenbach et al. (1991) |
| α-cypermethrin | 11.8 | 0.06 | Pansa et al. (2015) |
| λ-cyhalothrin | 6.9-11.9 | 0.06-0.1 | Pansa et al. (2015) |
| τ-fluvalinate | 10.4-16.2 | 0.07-0.04 | Pansa et al. (2015) |

Range (of decay rate): 0.1 – 0.5.

## Efficacy of label dose

In conversation with the Chemicals Regulation Division, UK, it was discussed that regulators would aim at 90% mortality following a spray. This is confirmed in two studies, that found between 80 and 95% mortality in the field from full rate sprays (Holland et al., 1997; Moreby et al., 2001).

# Resistance parameters

## Initial frequency of resistance

Insecticide resistance can arise through various mechanisms, including *de novo* mutations or standing variation (Hawkins, Bass, Dixon, & Neve, 2019). As such, the initial resistance frequency can vary from a single individual in a population, up to a large proportion of the population, but it is unlikely that the resistance will be detected in the field before it has reached a reasonably high level. We therefore – somewhat arbitrarily - consider a range for the initial frequency of resistance of each gene between and .

Range: 0.1 – 1x10-10.

## Resistance ratios of target-site resistance

While resistant insect strains have been found that have greater than 10000 times the LC50 of a susceptible strain (Gao et al., 2012), high resistance factors are frequently associated with combinations of many resistance mutations (Bass et al., 2014). The clearest method to find the resistance factor of only a single resistance mutation is to express the resistance mutation in an otherwise susceptible background, which can now be done using genome editing. Unfortunately, so far the majority of resistance mutations have been inserted into *Drosophila*, rather than into agricultural pests, but the resistance factor ought to still be representative.

The following are some resistance ratios that have been found after making target-site mutations in *Drosophila*.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Original Insect** | **Mutation** | **RR** | **Insecticide** | **Reference** |
| *Tuta absoluta* | G4946V | 91.3 | Flubendiamide | Douris et al. (2017) |
| *Tuta absoluta* | G4946V | 194.7 | Chlorothalonil | Douris et al. (2017) |
| *Tuta absoluta* | G4946V | 5.4 | Cyantraniliprole | Douris et al. (2017) |
| *Tuta absoluta* | I4790M | 15.3 | Flubendiamide | Douris et al. (2017) |
| *Tuta absoluta* | I4790M | 13.5 | Chlorothalonil | Douris et al. (2017) |
| *Tuta absoluta* | I4790M | 2.3 | Cyantraniliprole | Douris et al. (2017) |
| *Plutella xylostella* | Dα6 | 28.26 | Spinosad | Somers et al. (2015) |
| *Plutella xylostella* | A301S | 1.4 | Dieldrin | Guest et al. (2019) |
| *Plutella xylostella* | A301S | 2.7 | Fipronil | Guest et al. (2019) |

We do not consider low values of resistance ratios <10, since these do not increase to a significant level within the time span of the simulations.

Range: 10-1000

## Dominance of resistance genes

Genetic dominance dictates how resistant the heterozygote individuals are (main text, Figure 3). We allow this to vary between 0 and 1, to represent fully recessive to fully dominant expression.

Range: 0-1.

## Fitness cost of resistance

We have not found fitness costs linked directly to single target-site resistance genes. However there have been many studies that look at the fitness cost of resistance (e.g. Steinbach et al. (2017), Kliot and Ghanim (2012)). While Cao and Han (2006) found that the relative fitness of a resistant strain could be 70% lower than the susceptible strain, we limit the fitness cost to 10% reduction in the birth rate, otherwise the resistant strain does not increase in the population unless highly resistant (more than is realistic).

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