In the following case studies, the aim is not to re-analyse the publicly available datasets and scrutinise the findings. Our aim is to demonstrate how our proposed decision models can be used to extract a different kind of information from the available data - namely how specific decisions, and by extension order and timing where available of those decisions, alter the impact on the outcome of interest.

Case study 1: Wild pollinators in apple orchards

Apple orchards provide an excellent testing ground for our proposed methodology for multiple reasons. First, conventional practices are heavily reliant on intensive pesticide application regimes both before and during the growing season (1). Second, apples (*Malus pumila* Mill.) require cross-pollination - having a complex S-allele system in place to ensure this (2). Third, weather conditions not only impact fruit growth directly (for example chilling requirements (3), or sunshine hours during ripening (4)) but also pollinator activity indirectly (at very low temperatures or very wet conditions, pollinators are less active). These three aspects provide us with a system that is reliant on biodiversity, is affected by environmental variables both directly and indirectly, and contains multiple decision points for model testing.

In a conventional orchard, growers apply multiple types of compounds during the season. Fungicides (such as captan for example - one of the most commonly used fungicides on British apples (5)) are usually applied just before or during bloom. Especially before bloom, they can be combined with copper products to also act as bactericides, preventing for example cankers. In order not to impact pollinators, insecticides such as chlorpyrifos or glyphosate (6) are applied outside the flowering window (7). Finally, for crop load management, thinners are commonly used after the “June drop” - this is when the tree naturally aborts fruitlets to reduce the overall load (8,9). Thinners aim to extend this load-reduction in order to ensure that the tree is not damaged by branch breaks, and the remaining fruit can grow bigger, be of higher quality, and have sufficient access to sunshine for more homogenous ripening. Thinners are ideally applied after the natural load drop has occurred, which can last for weeks depending on growing conditions and cultivar interactions (10), and they are sometimes insecticides that are repurposed for thinning (7). This is important for wild pollinator studies as trees within an orchard are rarely perfectly synchronised, which means that although a percentage of flowers may still be open on some trees later than expected, thinners are applied overall, impacting pollinators. In a conventional setting, pollination will be done by strategic placement of honey bee hives throughout the orchard (11). In this case, insecticides and thinners are applied only after the removal of the hives from the orchard. Wild pollinators however, which can provide significant pollination services (12), cannot be sheltered from such applications.

The data set we propose to examine with our developed methodology was collected to study the impact of pesticides on wild pollinators for apple orchards in New York State with an additional focus on the size of nearby natural and semi natural habitats (13). The data contain the use intensity of different types of pesticides (e.g. fungicide or insecticide) applied in a breakdown relating to bloom timings (e.g. before bloom, during bloom, after bloom) for 19 orchards (16 of which were replicated for two years), temperature conditions during sampling, flowering levels during sampling, as well as characteristics of the orchard and nearby natural habitats. In each sampling time, transect lines were used to collect and identify pollinators. As the position of each orchard is available, we can also combine with overall weather data from nearby stations, made publicly available through the National Oceanic and Atmospheric Administration (NOAA), however as the precise dates of each sampling are not available we would only be able to approximately estimate timings by working backwards using growing degree days and the estimates of flowering within each orchard.

As a starting model for the New York Orchards dataset we determine three decision points relating to bloom timings during which the growers have a variety of options:

* Before bloom decision point - Apply Fungicide, Apply Insecticide, Apply Both, Apply Nothing
* During bloom decision point - Apply Fungicide, Apply Insecticide, Apply Thinner, Apply Two of the Three, Apply All, Apply Nothing
* After bloom decision point - Apply Insecticide, Apply Thinner, Apply Both, Apply Nothing

The specific aim would be to use our model to study how the order and choice of pesticides impacts the richness and abundance of wild bees. Extensions of the model can then focus on use intensity, approximate weather conditions, and orchard scaling factors. Following that we can simulate from the built model to examine how altering specific decisions under given conditions would impact the wild pollinators.

Case study 2: Farm Scale evaluations

The “Farm Scale Evaluation Datasets” (14,15) contain data on four crops grown in multiple farms, with records of the impact of growing practices on biodiversity and overall crop yield. The experiment was originally conducted to compare the ecological impact of genetically modified and conventional crops and the data contain Maize, Beet, Spring Oilseed Rape, and Winter Oilseed Rape records with an average of 65 fields for each crop. Collected data include herbicide application timings, percentage cover of weeds, height of crop, biodiversity counts, and yields. Other than the collected conditions available within the datasets, we can use the extensive historical weather station data available from the Met Office, for more accurate estimation of environmental conditions. This collection provides an ideal testing ground for some of the theoretical concepts that the PI has already been developing (CITE J’S MANUSCRIPT) such as ownership, control of a step, influence, knowledge, and foresight. Furthermore, the availability of both yield and biodiversity data permits the exploration of utility functions that balance between biodiversity and agricultural output. Many of the weeds that are targeted by herbicides are pollinator friendly (16), therefore differences in decisions by the grower could indirectly affect the levels of presence/absence of pollinators through the season. The dataset contains pollinator counts from monthly transect line surveys that were conducted during the growing season. We propose to model the growing season as an interaction between three decision makers: the grower, the plants, and the environment.

We intend to focus as a starting point on the grower’s decision to apply herbicide at a particular time point, a decision that is dependent on multiple factors and their combination. In order to model this complex process, we need employ proxies that could be used to identify the grower’s drivers for a particular action. The first proxy is the observation of weed levels at different points in time, for which we can use the weed percentage cover estimates that are available for each field at different timepoints. The second proxy would be state of the crop - later in the season the crop may not be as affected by weeds as it would be earlier in the season. Factors for which we do not have proxies but are important for the decision-making process are how risk averse a grower is, or their experience with a particular crop. Plants in this case are considered decision makers - given certain specific conditions plants decide to grow. Although the plant decisions are predictable, they are only so when linked with the external force that is the environment, weather being of primary importance. In the small scale, the environmental decisions (such as precipitation) take no input from the grower-plant system but they influence plant growth.

The specific aim of the initial model would be to investigate how herbicide application decisions are impacting a joint outcome of biodiversity and yield. Extensions of this can focus on finetuning concepts of foresight for the grower by exploring the weather data available to us: for example at the time of the weed cover survey, we may give the grower foresight of weather conditions for the next week, and study whether the application of herbicide was delayed or not based on that knowledge and how that may have impacted overall outputs.

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