Artificially Intelligent Foraging

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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Abstract

Bumble bees (*bombus spp.*) are significant pollinators of many plants, and are particularly attracted to mass-flowering crops such as Oilseed Rape (*Brassica Napus*), which they cross-pollinate. *B. napus* is both wind and insect-pollinated, and whilst it has been found that wind is its most significant pollen vector, the influence of bumble bee pollination could be non-trivial when bee densities are large. Therefore, the assessment of pollinator-mediated cross-pollination events could be important when considering containment strategies of genetically modified (GM) crops, such as GM varieties of *B. napus*, but requires a landscape-scale understanding of pollinator movements, which is currently unknown for bumble bees.

I developed an *in silico* model, entitled HARVEST, which simulates the foraging and consequential inter-patch movements of bumble bees. The model is based on principles from Reinforcement Learning and Individual Based Modelling, and uses a Linear Operator Learning Rule to guide agent learning. The model incoproates one or more agents, or bees, that learn by 'trial-and-error', with a gradual preference shown for patch choice actions that provide increased rewards.

To validate the model, I verified its ability to replicate certain iconic patterns of bee-mediated gene flow, and assessed its accuracy in predicting the flower visits and inter-patch movement frequencies of real bees in a small-scale system. The model successfully replicated the iconic patterns, but failed to accurately predict outputs from the real system. It did, however, qualitatively replicate the high levels of inter-patch traffic found in the real small-scale system, and its quantitative discrepancies could likely be explained by inaccurate parameterisations. I also found that HARVEST bees are extremely efficient foragers, which agrees with evidence of powerful learning capabilities and risk-aversion in real bumble bees.

When applying the model to the landscape-scale, HARVEST predicts that overall levels of bee-mediated gene flow are extremely low. Nonetheless, I identified an effective containment strategy in which a 'shield' comprised of sacrificed crops is placed between GM and conventional crop populations. This strategy could be useful for scenarios in which the tolerance for GM seed set is exceptionally low.

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Parameter	Identifier
ξ	Proportion of sink patch's seed with source patch paternity mediated by cross-pollination
E	Fraction of pollinators arriving at sink from source
Ψ	Number of fruits fully fertilised in sink with source pollen by each pollinator in a sink visit
b	Total sink fruits fertilised by each pollinator in a sink visit
B	Number of bees in the grid
B_E	Estimated number of bees in the grid
L	Number of patches in landscape
Q	Initial quality of patches
Q(i)	Actual quality of patch i
q(i)	Estimated quality of patch i
β	Sensitivity to individual flower sample
s(i)	Value of the reward from latest sample in patch i
v(i, j)	Action-value for visiting patch j when currently in patch i
C	Bee's nectar carrying capacity
c	Bee's remaining nectar carrying capacity
h	Flower handling time
t(i, j)	Flight time between patches i and j
F_i	Number of flowers in patch i
I_i	Replenishment interval for patch i
P(x)	Bee's foraging efficiency in foraging bout x
G(x)	Elapsed time on the global clock since foraging bout x began
R_{full}	Reward (in nectar units) offered by a full flower
R_{empty}	Reward (in nectar units) offered by an empty flower
T	Total time spent observing in empirical study
T_B	Total time (in seconds) spent actively observing bee activity in empirical study
a	Proportion of array observed during an empirical study session

Definitions

Dry (D) Patch	A patch of flowers that is droughted
Floral Catchment	The set of patches representing the surrounding landscape external to the sink and source populations.
HARVEST	**H**arvesting **A**nimal **R**einforced **V**alues and **Est**imates. A Reinforcement Learning-based foraging model.
Omniscient Bee	A HARVEST bee that is always aware of the true quality of patches in the landscape
Performance	The quantified foraging efficiency of a HARVEST bee, expressed in terms of the amount of resource gathered divided by the time taken to do so
Sacrificial Shield	An array of resource sites whose genetic purity is sacrificed to preserve the genetic purity of another population.
SWIPT	System-wide inter-patch traffic. A measure of the level of movement by bees on average within the foraging system.
Wet (W) Patch	A patch of flowers that is kept healthy by being regularly watered

Abbreviations

%	Percentage
µ	Micro
AI	Artificial Intelligence
ANN	Artificial Neural Network
B. napus	*Brassica napus*
BL	*Bombus lapidaries*
BP	*Bombus pratorum*
BT	*Bombus terrestris*
D	Dry
DEFRA	Department for Environment, Food and Rural Affairs
EU	European Union
GM	Genetically Modified
h	Hours
HARVEST	Harvesting Animal Reinforced Values and Estimates
HOOFS	Hierarchical Object Oriented Foraging Simulator
IBM	Individual Based Model
IFD	Ideal Free Distribution
IP	Iconic Pattern
JST	Job Search Theory
km	Kilometre
l	Litre
LS	Landscape-Scale
m	Metre
MVT	Marginal Value Theorem
OFT	Optimal Foraging Theory
PMF	Plant Molecular Pharming
RL	Reinforcement Learning
RNEI	Rate of Net Energetic Intake
s	Seconds
S.E.	Standard Error
SS	Sacrificial Shield
t.u.	Time Unit
TDR	Threshold Departure Rule
W	Wet