Supplementary Material

Part 1. Tables and figures mentioned in the text

Table S1. The general temperature ranges

Month	Temperature range (sunny)	Temperature range (cloudy)	Day of simulation
January	6-22°C	6-12°C	1-30
February	10-26°C	12-14°C	31-60
March	14-28°C	13-16°C	61-90
April	16-30°C	14-18°C	91-120

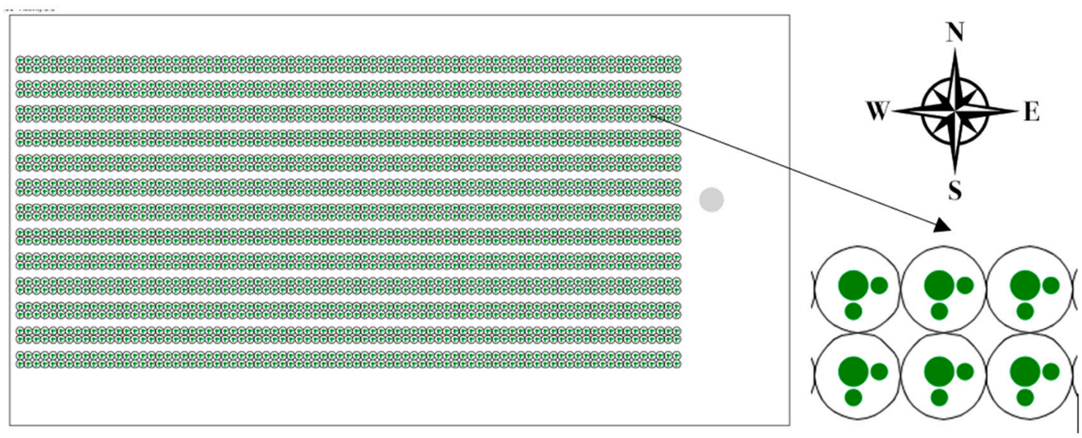


Figure S1. A simulated strawberry greenhouse. The out rectangle represents the greenhouse boundary. Inside the boundary, black open circles represent strawberry plants, green dots represent different inflorescences. Green dots of different sizes represent different inflorescence rank. In the east open site of the greenhouse, the grey dot represents bee hive.

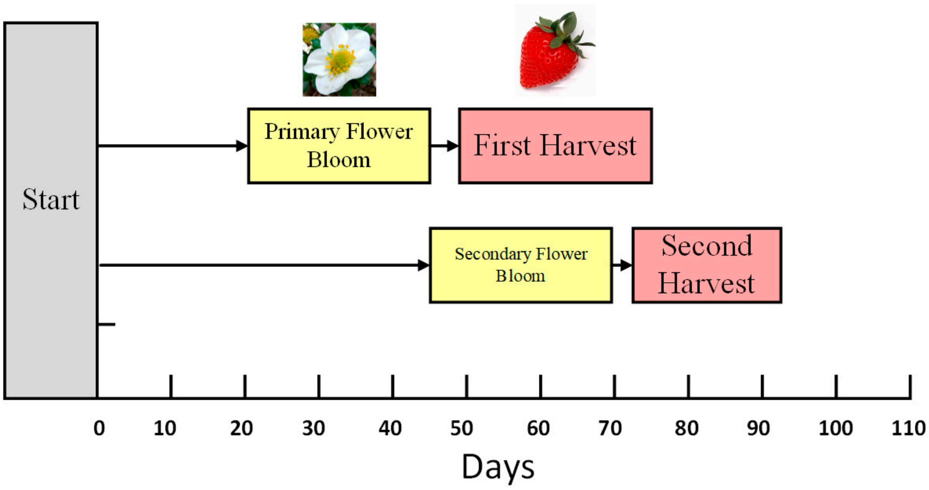


Figure S2. Timing schedule for the two harvests of strawberry simulation

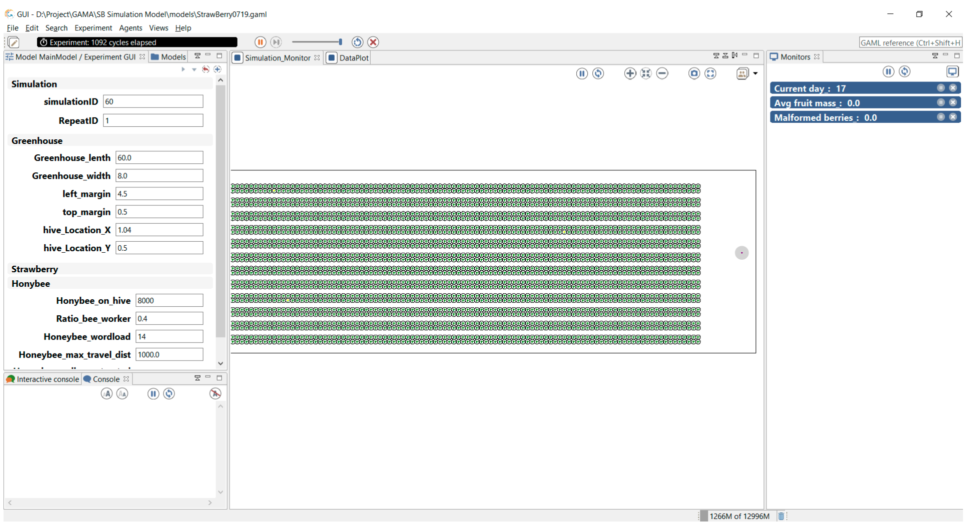
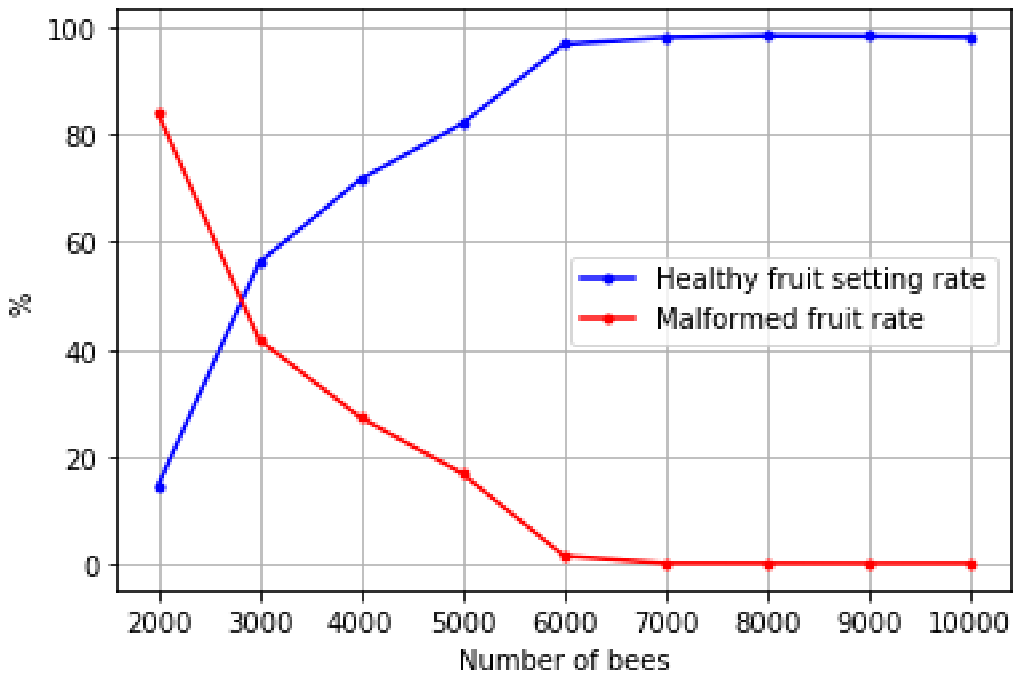


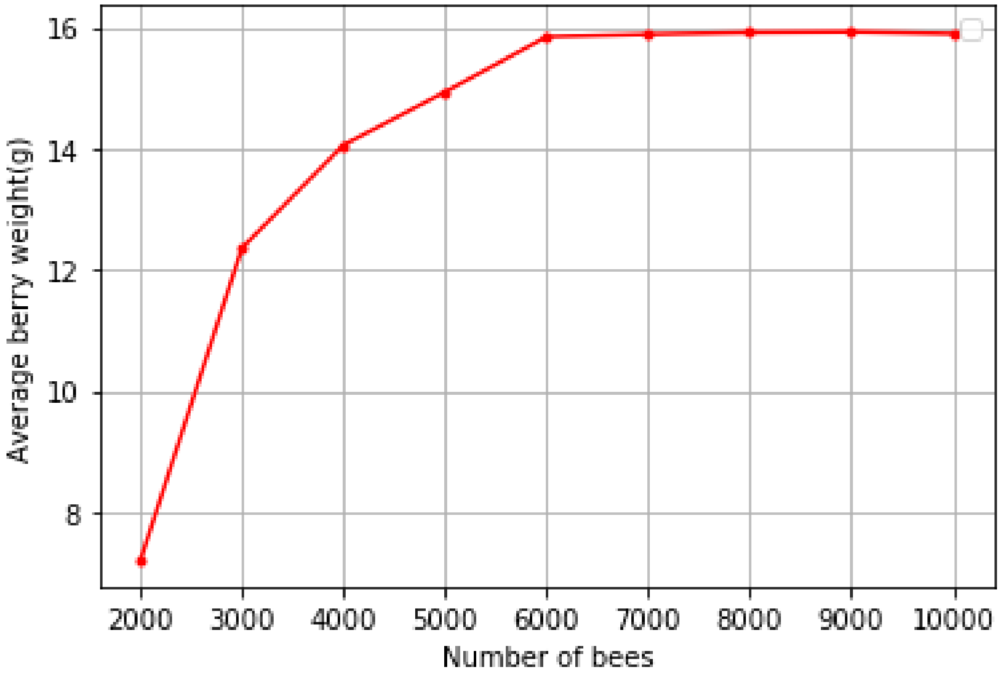
Figure S3. Friendly graphical user interface of the simulation model in GAMA

Table S2. Simulated strawberry fruit set, quality and yield with various bee densities (80m long)

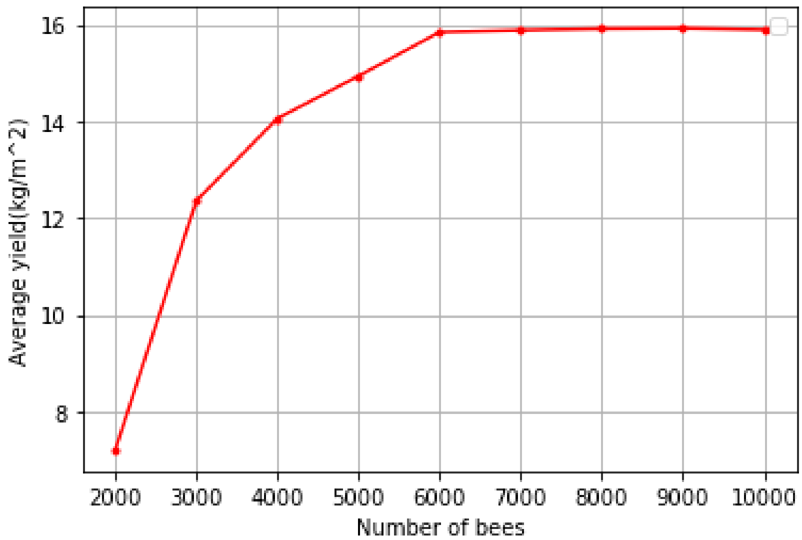
Bee density	Number of bees	Average rate of fruit set	Average berry weight(g)	Average malformed fruit rate	Average yield (kg/m^2)
0.21	2,000	5.00 %	4.69	93.06 %	1.03
0.32	3,000	18.42 %	7.94	79.87 %	1.71
0.42	4,000	51.76 %	11.85	45.94 %	2.53
0.53	5,000	65.45 %	13.37	33.21 %	2.84
0.64	6,000	73.18 %	14.17	25.71 %	3.03
0.75	7,000	86.02 %	15.24	12.68 %	3.24
0.85	8,000	94.27 %	15.72	4.08 %	3.36
0.96	9,000	98.28 %	15.95	0.23 %	3.39
1.00	9,360	98.27 %	15.94	0.22 %	3.39
1.07	10, 000	98.25 %	15.96	0.21 %	3.39
1.18	11, 000	98.30 %	15.95	0.16 %	3.38
1.28	12, 000	98.30 %	15.95	0.16 %	3.39



(a) Average healthy fruit setting rate and malformed fruit rate



(b) Average berry weight

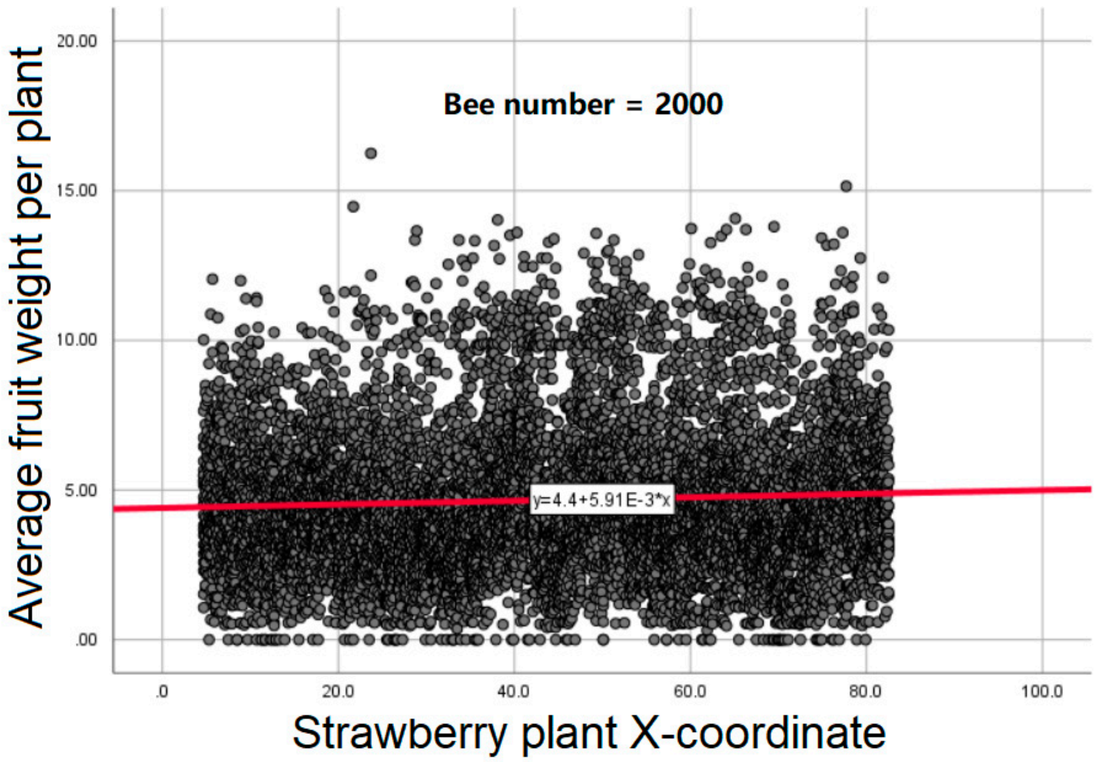


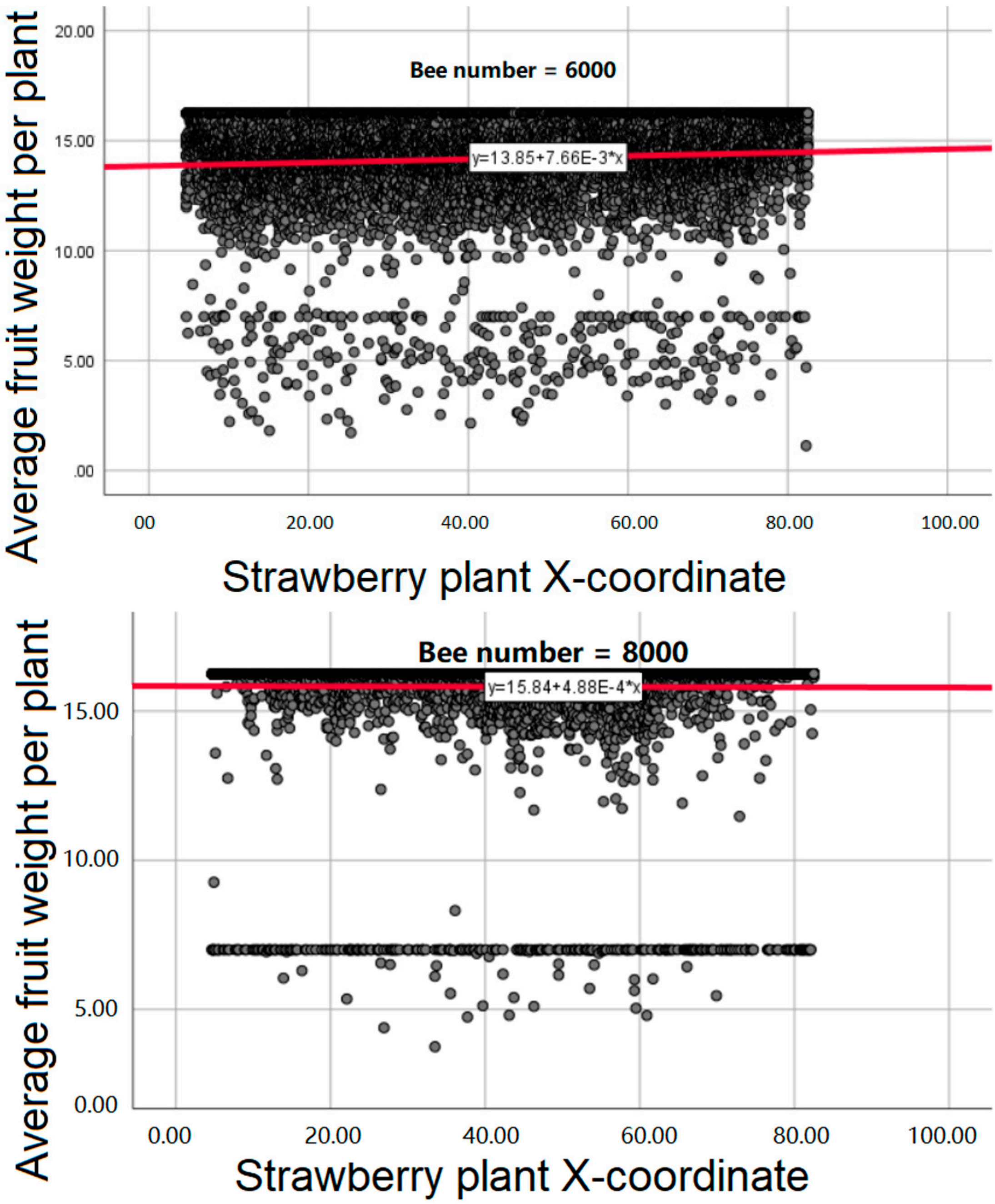
(c) Average yield

Figure S4. The relationship between bee abundance and fruit quality in greenhouse with a length of 60m. It can be seen that with the increase in bee abundance, the quality of strawberry fruit is also constantly improving. However, when the bee number reaches about 6500, this improvement is not significant.

Table S3. Simulated strawberry fruit set, quality and yield with various bee densities (60 m long)

Bee density	Number of bees	Average fruit setting rate	Average berry weight(g)	Average malformed fruit rate	Average yield (kg/m^2)
0.30	2,000	14.53	7.21	83.87 %	1.47
0.45	3,000	56.16	12.36	41.75 %	2.51
0.60	4,000	71.60	14.06	27.25 %	2.86
0.74	5,000	81.95	14.94	16.85 %	3.04
0.89	6,000	96.72	15.86	1.57 %	3.22
1.00	6,720	96.96	15.86	0.50 %	3.21
1.04	7,000	97.97	15.89	0.19 %	3.23
1.19	8,000	98.32	15.92	0.18 %	3.24
1.33	9,000	98.22	15.93	0.16 %	3.24
1.48	10, 000	98.01	15.90	0.17 %	3.23





(a) Scatter diagram with different bee abundances

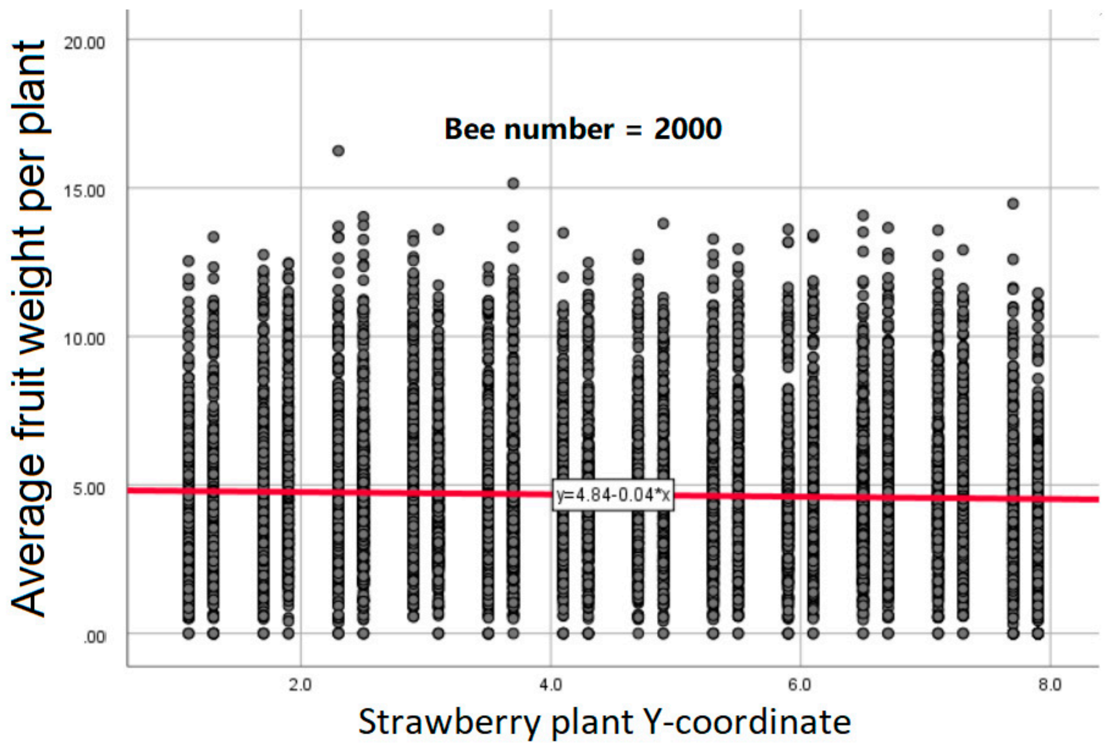
ANOVA

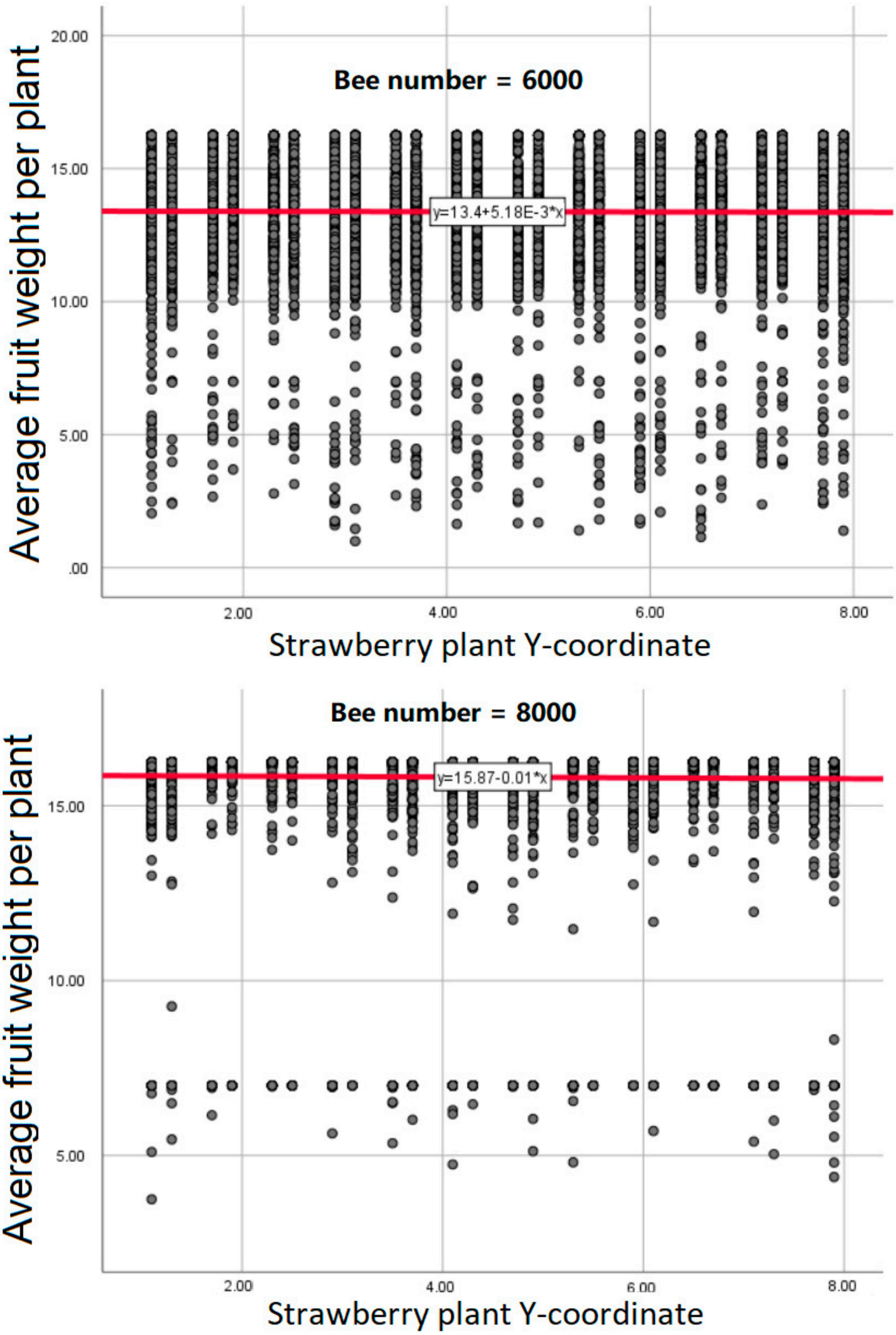
c.clone_fruitmass_mean

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1625.209	389	4.178	1.325	.000
Within Groups	28281.995	8970	3.153		
Total	29907.204	9359			

(b) ANOVA analysis with the bee number of 8000

Figure S5. Diagram to show the relationship between strawberry plant X-coordinate and fruit quality. High X-value represents short distance to the hive located in east side of greenhouse. It can be seen that the fruit weight distribution on X-coordinate was not uniform and there was a significant difference (P < 0.05).





(a) Scatter diagram with different bee abundances

ANOVA

c.clone_fruitmass_mean

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	81.283	23	3.534	1.106	.328
Within Groups	29825.921	9336	3.195		
Total	29907.204	9359			

(b) ANOVA analysis with the bee number of 8000

Figure S6. Diagram to show the relationship between strawberry plant Y-coordinate and fruit quality. It can be seen that the fruit weight distribution on Y-coordinate was basically uniform and there was no significant difference ($P > 0.05$).

Table S4. Impacts of diverse hive locations with only one hive (bee number is 4000)

Location of hive	Average berry weight(g)	Malformed fruit rate (%)
Middle of east side	11.85 ± 0.32a	45.92 % ± 2.416a
Middle of west side	11.80 ± 0.31a	45.66 % ± 1.92a
Greenhouse center	11.93 ± 0.30a	46.89 % ± 1.98a
Middle of south side	11.84 ± 0.27a	45.62 % ± 2.07a
Middle of north side	11.86 ± 0.33a	45.92 % ± 1.89a

Means ± standard error (n=10) within each column followed by the same letter are not significantly different ($P>0.05$)

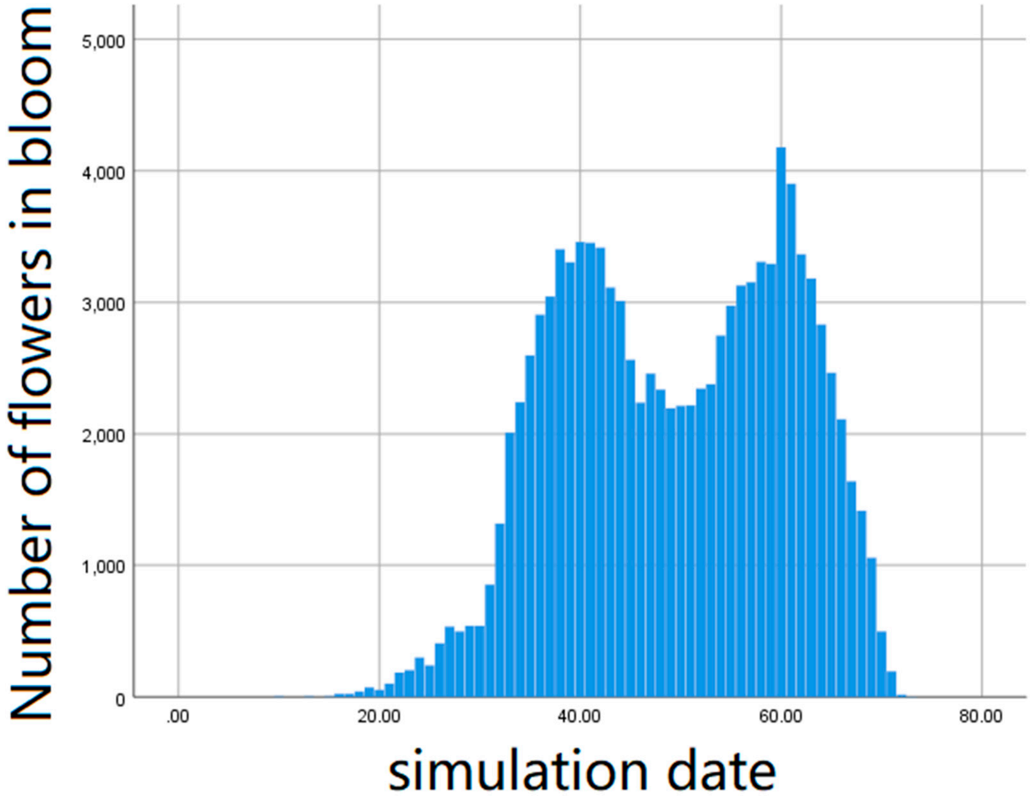
Part 2. Simulated spatial pattern of strawberry plants in greenhouse

(a)

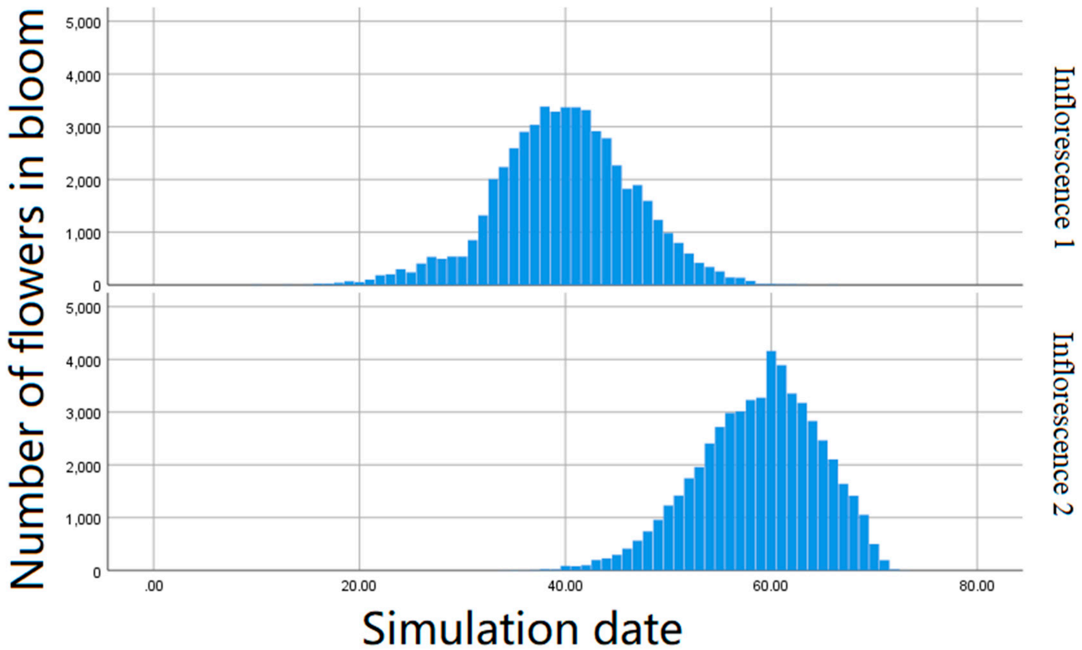
(b)

Figure S7. (a) The real strawberry greenhouse; (b) Simulated spatial pattern of strawberry plants in greenhouse.

Part 3. Simulated strawberry phenology within a field

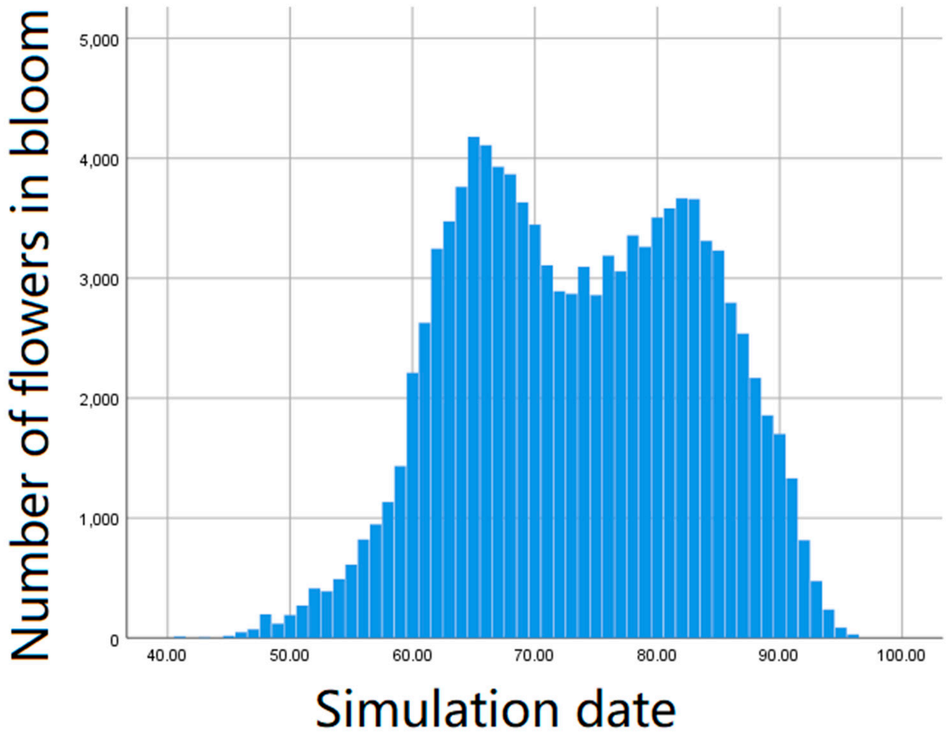


(a) Not grouped by inflorescences in simulation

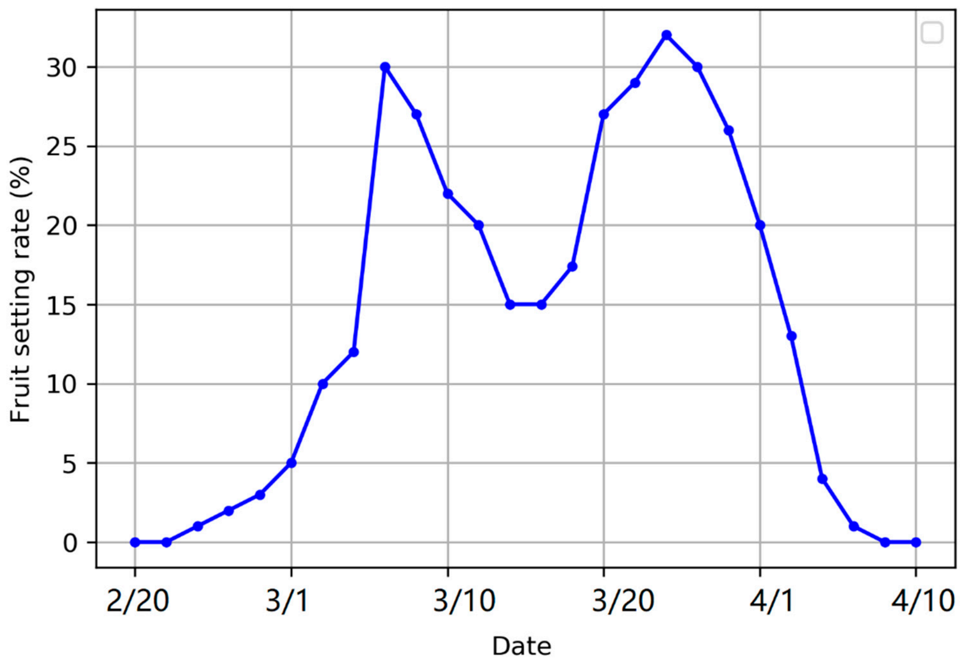


(b) Grouped by inflorescences in simulation

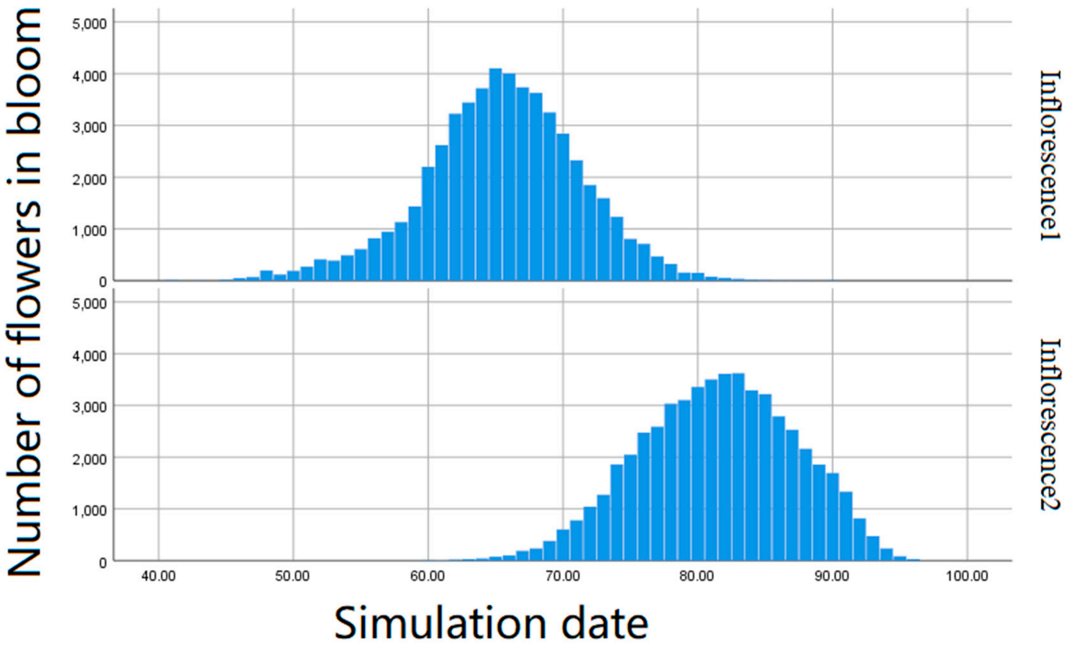
Figure S8. Simulated frequency distribution of strawberry blooming dates. The X-axis represents the simulation date, and the Y-axis represents the corresponding flower quantity. It can be seen that strawberries mostly bloom in two periods due to inflorescence rank.



(a) Not grouped by inflorescences in simulation

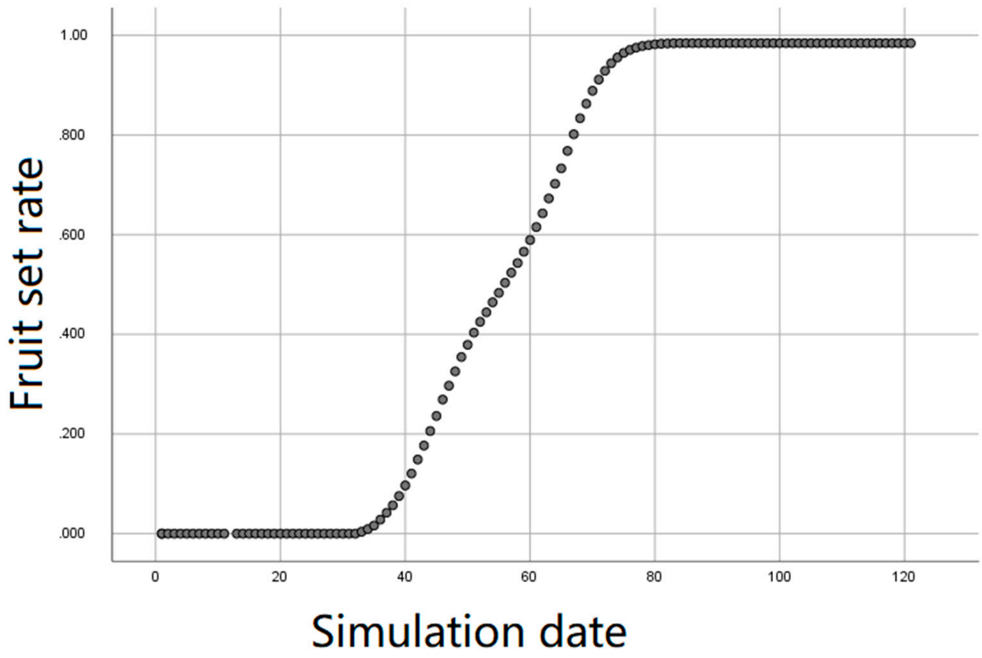


(b) Real fruit setting rate of strawberry in greenhouse planting collected from field observations

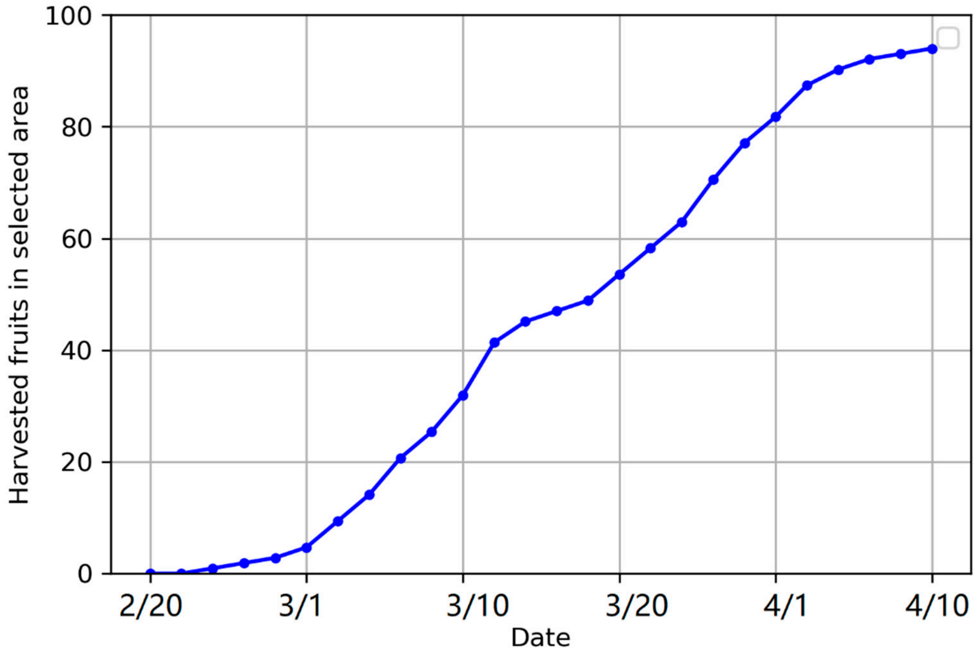


(c) Grouped by inflorescences in simulation

Figure S9. Simulated frequency distribution of strawberry fruiting dates in simulation (a, c) and practical greenhouse planting (b). The X-axis represents the planting date. The Y-axis represents the corresponding flower quantity (a, c) or real fruit setting rate (b). It can be seen that simulation results largely agree with the practical planting experience.



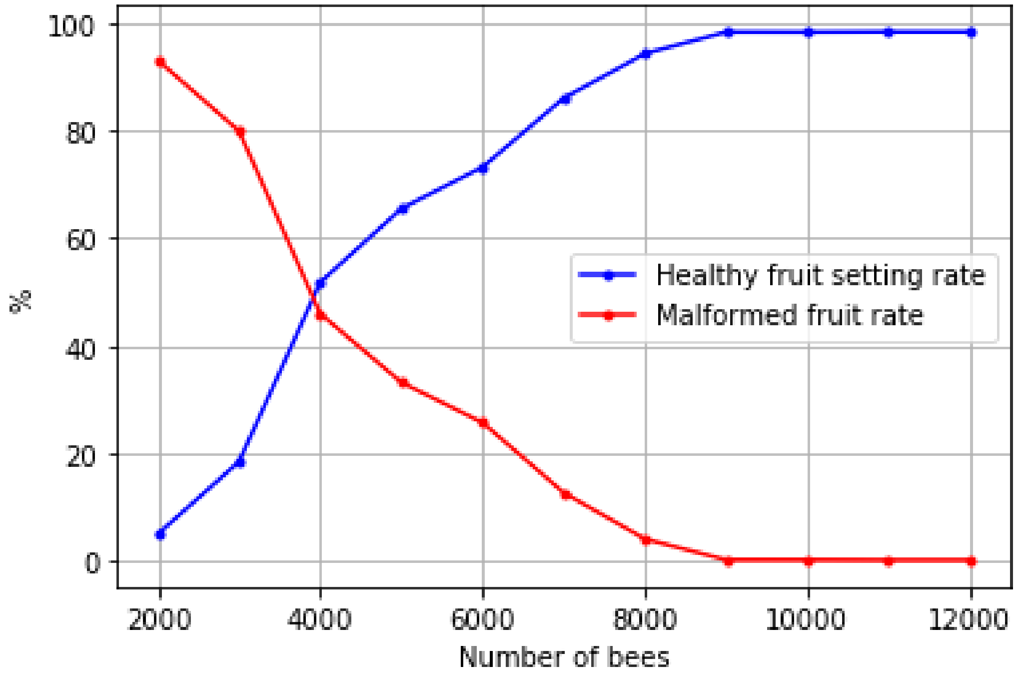
(a) Accumulated fruit setting rate in simulation



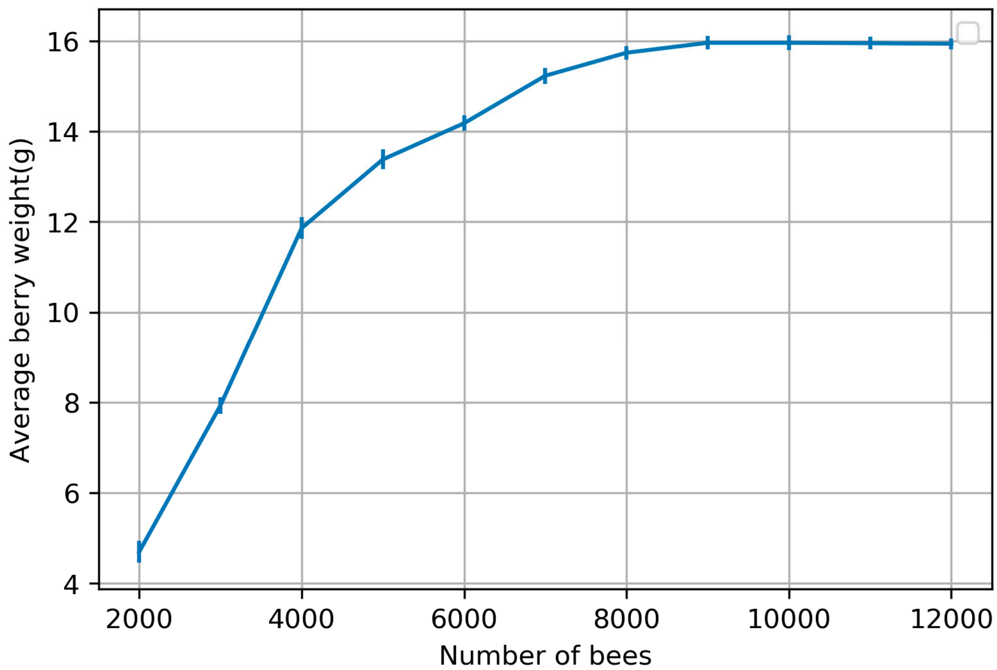
(b) Real observed harvested fruits information in greenhouse quadrat

Figure S10. Accumulated strawberry fruit setting information in simulation and practical planting. It can be seen that strawberry fruiting is a continuous process.

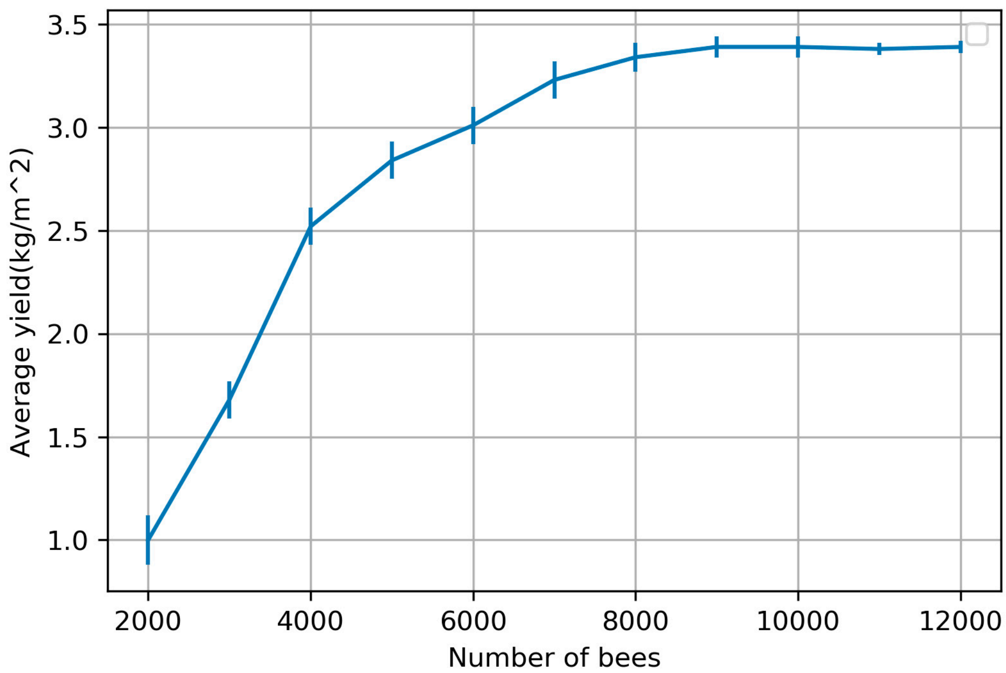
Part 4. The relationship between bee abundance and fruit quality



(a) Average healthy fruit setting rate and malformed fruit rate



(b) Average berry weight



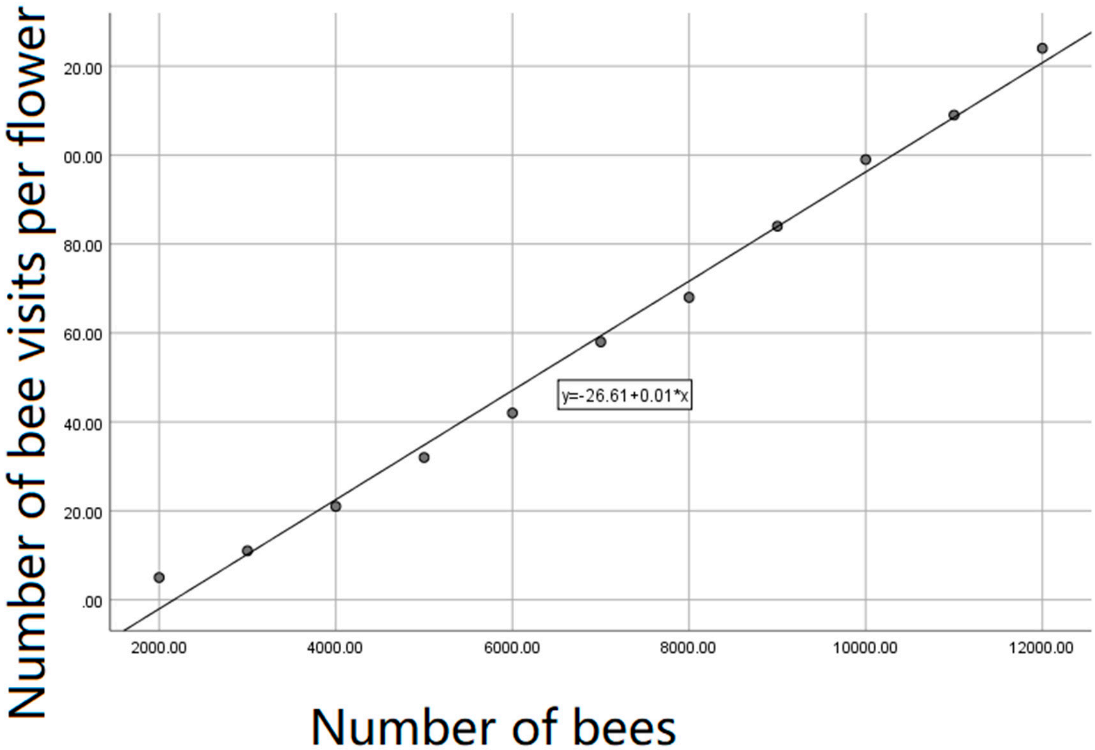
(c) Average yield

Figure S11. The relationship between bee abundance and fruit quality in greenhouse with a length of 80m. It can be seen that with the increase in bee abundance, the quality of strawberry fruit is also constantly improving. However, when the bee number reaches about 9000, this improvement is not obvious. Because this simulation only considers pollination and thus the malformed fruit rate is lower than in practical planting [17].

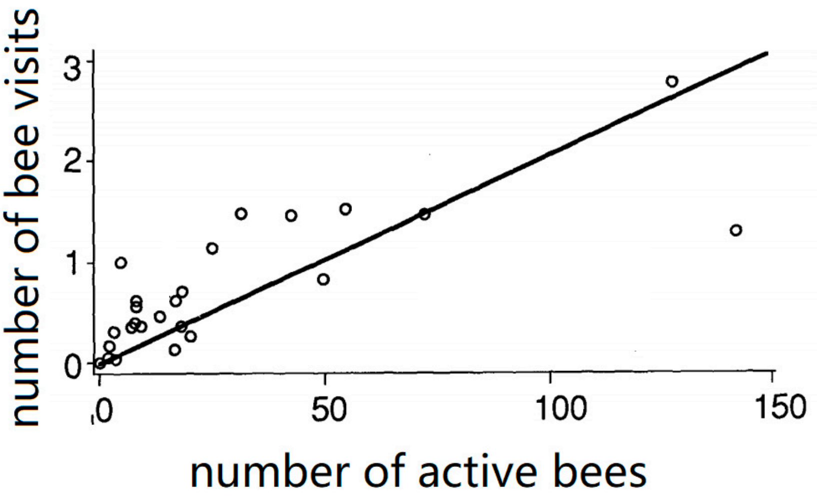
Part 5. Bee abundance and average number of bee visits per flower

Table S5. Bee abundance and average number of bee visits per flower

Number of bees	Number of bee visits per flower
2,000	5
3,000	11
4,000	21
5,000	32
6,000	42
7,000	58
8,000	68
9,000	84
10, 000	99
11, 000	109
12, 000	124



(a) The fitted linear function based on data in Table 1



(b) The linear relationship in reference [6]

Figure S12. Diagram to show the relationship. It can be seen there is a linear relationship between bee abundance (X) and average number of bee visits per flower (Y) and we can describe the relationship by formula: Y=26.61+0.01*X. As shown in [6], the average number of bees visits to a flower can be presented as a linear function of active bee number.

Part 6. Relationship between bee visit number and fruit quality

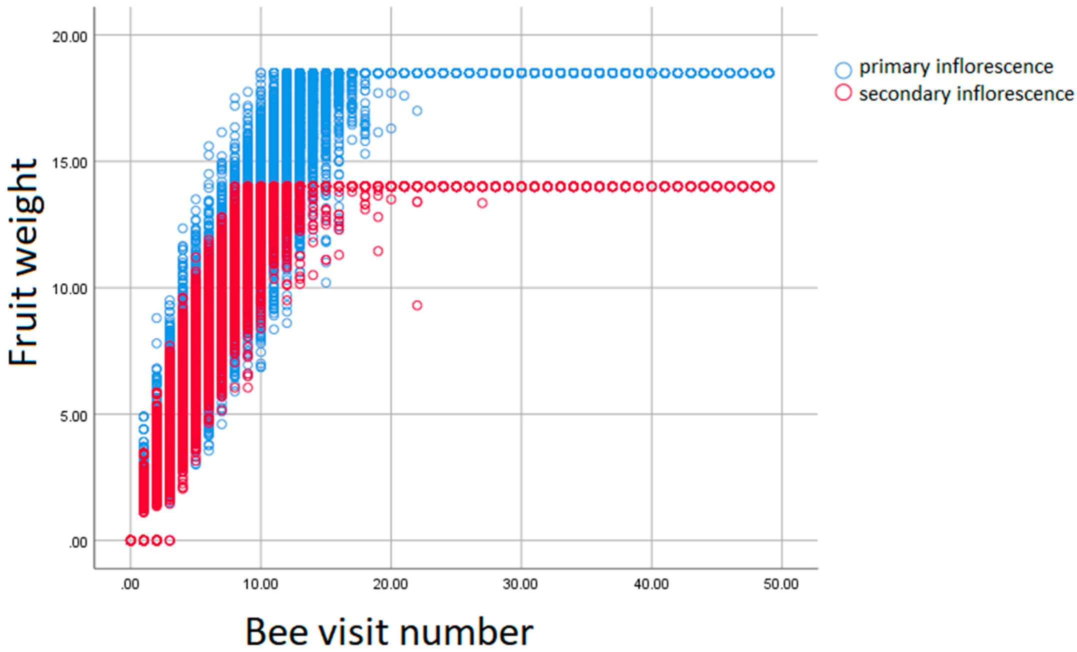
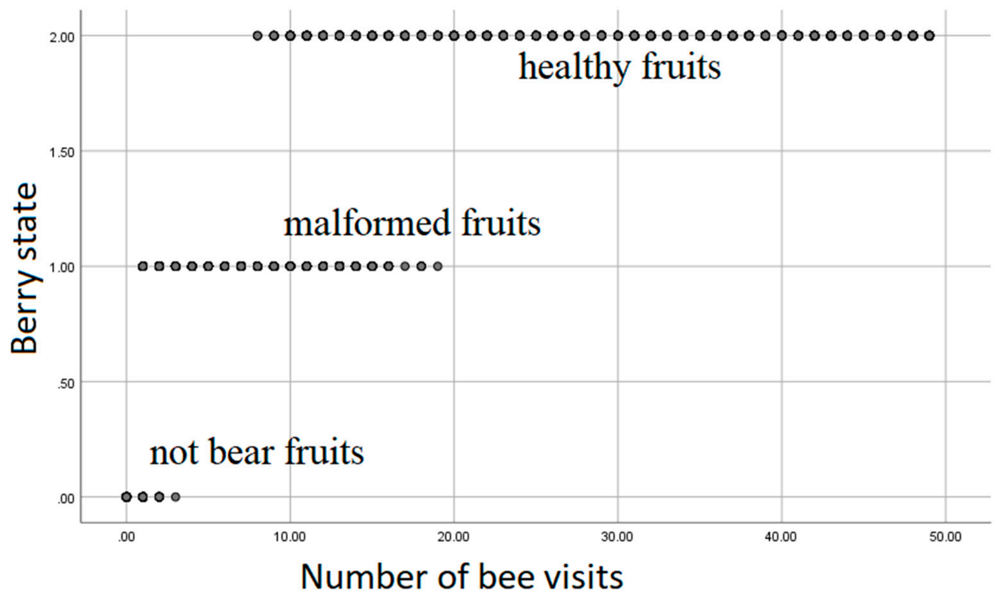
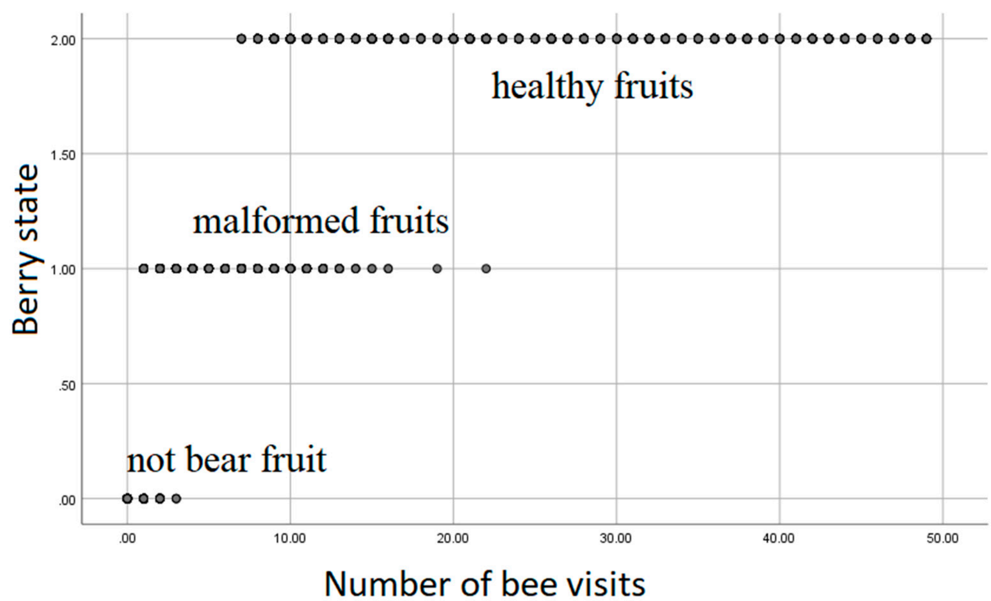


Figure S13. Diagram to show the relationship between bee visit number and fruit weight. Red dots are flowers in secondary inflorescences and blue dots are flowers in primary inflorescences. It can be seen that before the fruit weight reaches the peak, the relationship can be described as basically linear, which is consistent with the reference [4, 6].



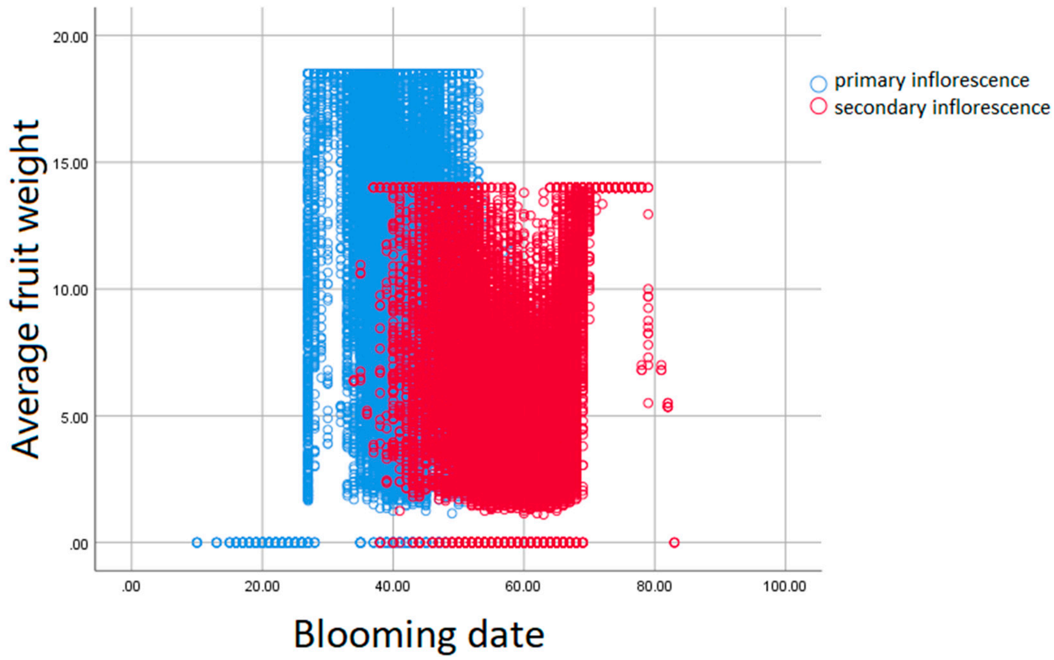
(a) Primary inflorescence



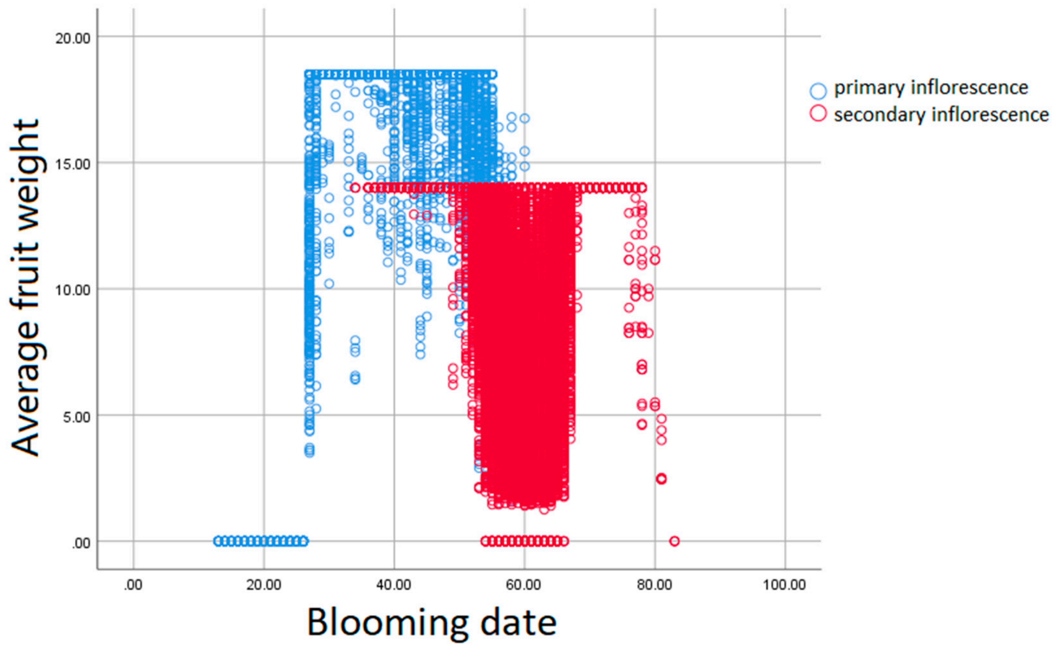
(b) Secondary inflorescence

Figure S14. Diagram to show the relationship between bee visit number and malformed fruit information. In Y-axis, figure 2 presents the healthy fruit with high commercial value, figure 1 presents the malformed fruit, and figure 0 presents flowers which not bear fruit. It can be seen that the malformed fruit rate negatively correlates with the bee visit number.

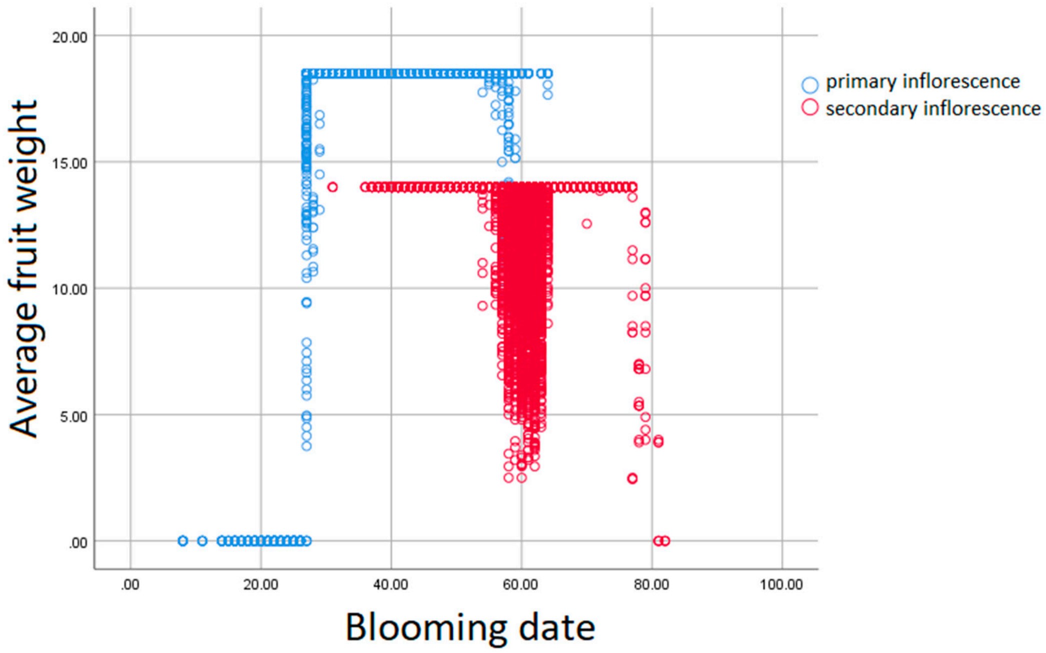
Part 7. Relationship between blooming time and fruit weight



(a) The number of bees is 3000



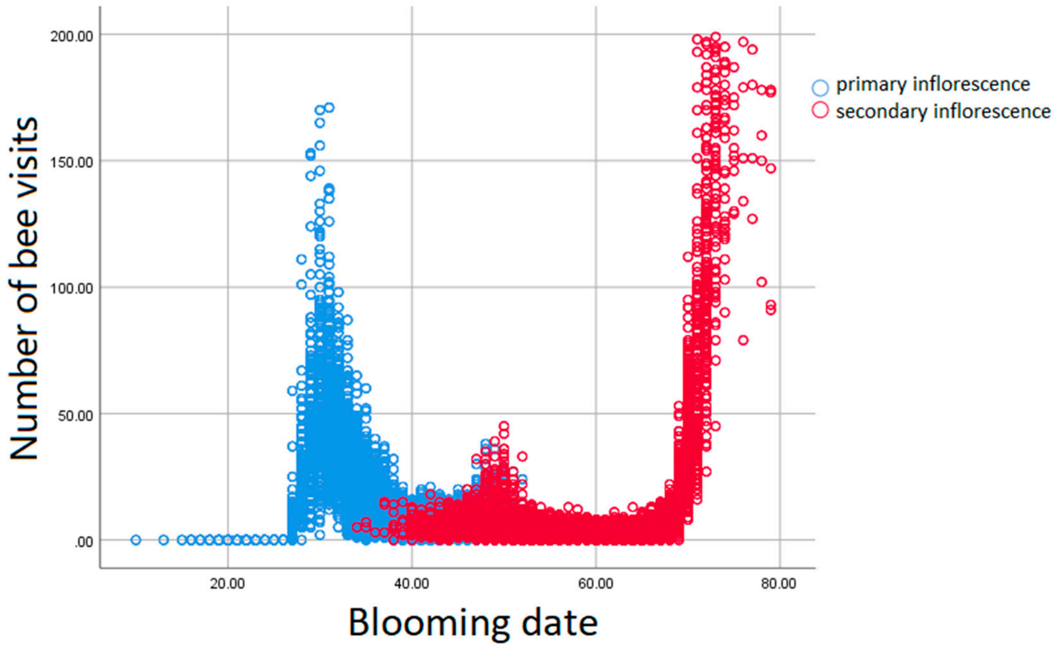
(b) The number of bees is 5000



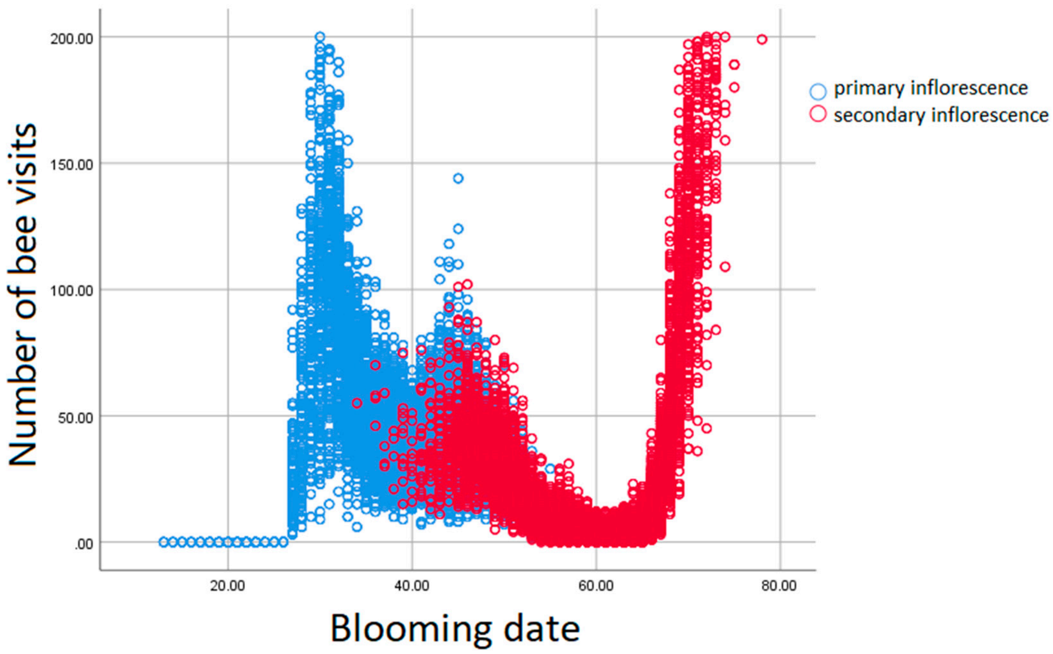
(c) The number of bees is 8000

Figure S15. Diagram to show the relationship between blooming time and fruit weight. These three figures show the changing trend with different bee abundances. It can be seen that there are some blank areas in the cluster of the dots. For the primary flowers, the pollen grains are insufficient when flowers bloom too early, and they may compete with the secondary flowers for bee resources when flowers bloom too late with the result that growth of flowers blooming in middle period is better. For secondary flowers, the number of flowers blooming in middle period is large, resulting in competition for bee resources among them, so the growth will be influenced adversely, and those blooming in the early and late periods grow better.

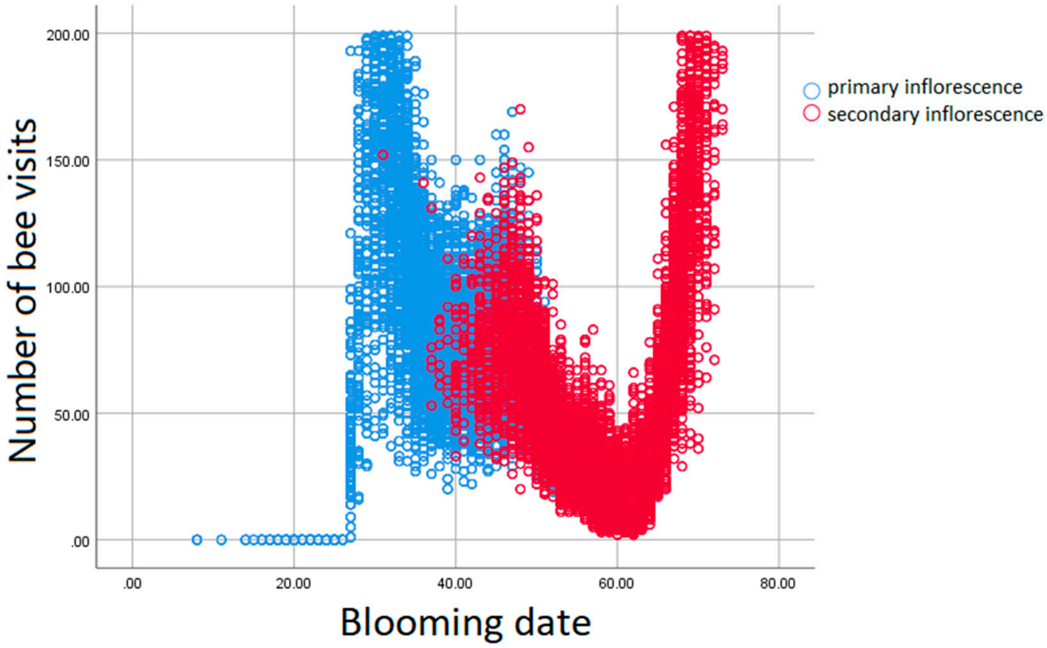
Part 8. Relationship between blooming time and bee visit number



(a) The number of bees is 3000



(b) The number of bees is 5000



(c) The number of bees is 8000

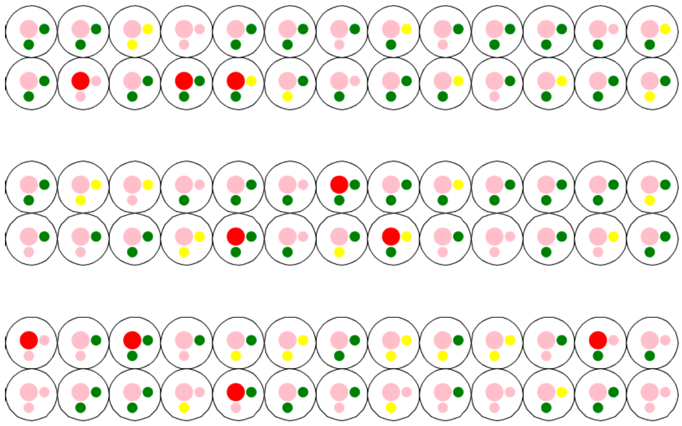
Figure S16. Diagram to show the relationship between blooming time and bee visit number. It can be seen that fruit quality improves with the increase in bee visit number. Therefore, we can get a similar conclusion that primary flowers blooming in middle period and secondary flowers blooming in early or late periods will grow better.

Part 9. Simulated strawberry growth and phenology

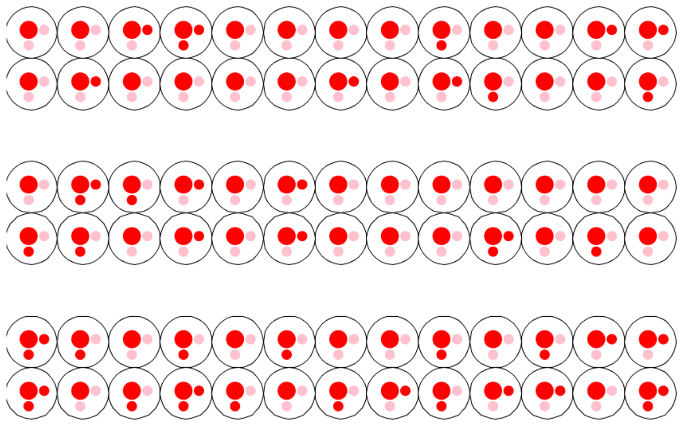
This model allows users to explore how various factors, including bee density, pollen compatibility, pollen viability, stigma receptivity, bed spacing, hive location, changes in weather conditions and foraging behavior as well as greenhouse environment influence the pollination process and fruit quality, particularly healthy fruit setting rate, average berry weight, malformed fruit rate and average yield. The graphical user interface of software lowers barriers to using simulation for researchers or interested growers with little or no experience in modelling, and enables them to test hypotheses, develop theories and assess strawberry management strategies. Based on this firmly validated model, we proposed some planting suggestions for strawberry growers.

(a) 20^{th} day in simulation

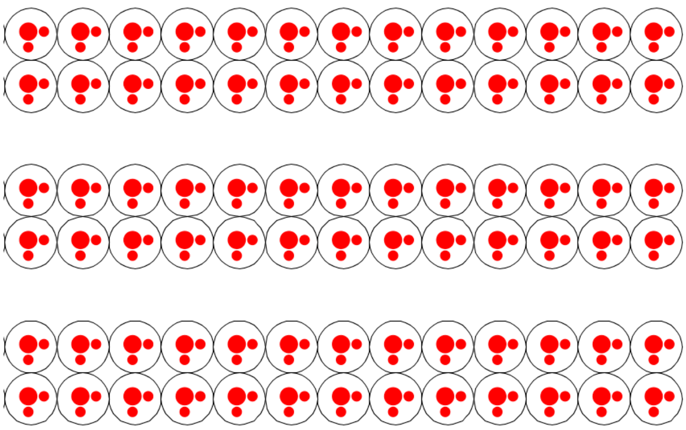
(b) 40^{th} day in simulation



(c) 60th day in simulation



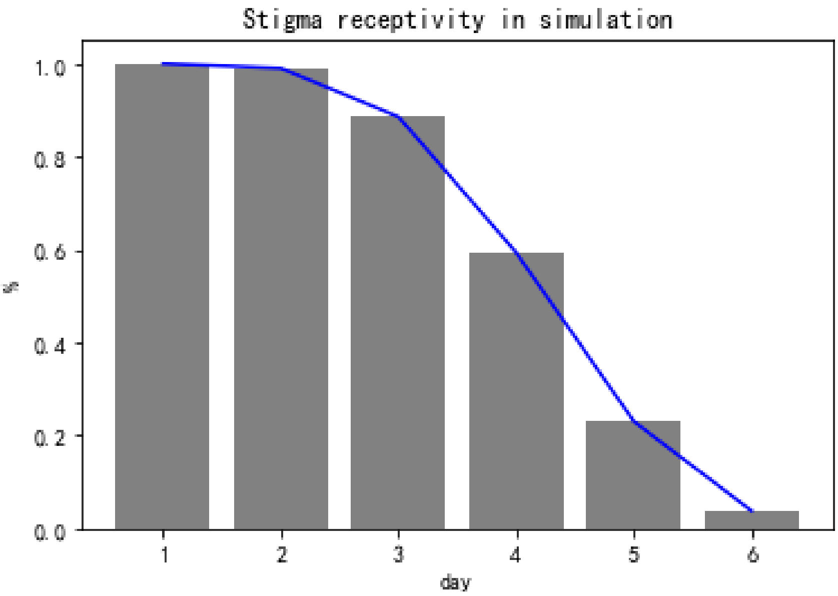
(d) 80th day in simulation



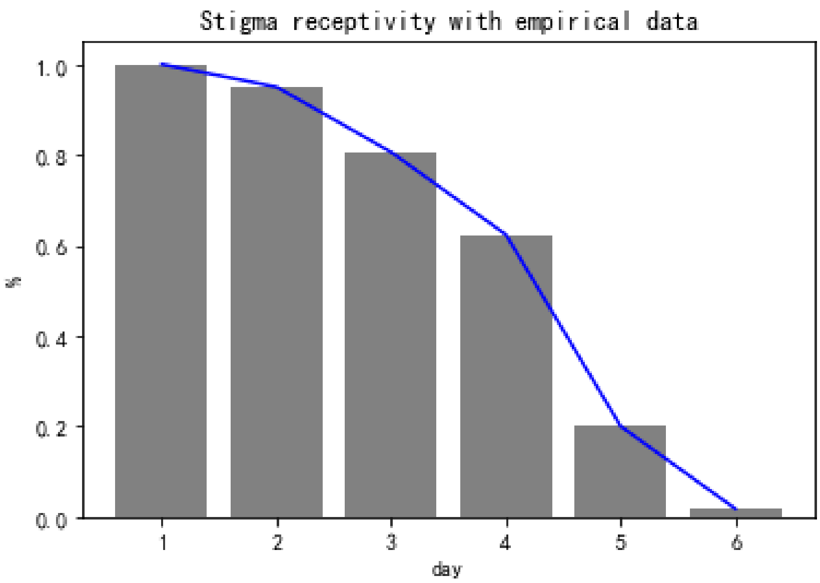
(e) 100th day in simulation

Figure S17. Simulated strawberry growth in greenhouse on different dates respectively. The growing process is continuous. Strawberry buds, flowers and fruits will be present in the greenhouse at the same time. In these figures, green dots represent inflorescences in bud stage, red dots represent inflorescences in bloom, pink dots represent inflorescences in fruit growth stage and red dots represent inflorescences in ripeness stage. The primary flowers bloom earlier and the secondary flowers bloom later.

Part 10. Simulated stigma receptivity



(a) Stigma receptivity in simulation



(b) Stigma receptivity with empirical data

Figure 18. Stigma receptivity is mainly determined by flower age, and the viability is peak within three days of blooming and sharply declines in 5 days.

Part 11. Artificial pollination

Figure S19. In artificial pollination, growers can brush the outer edge (stamens or anthers) of the flower with a paintbrush to move pollen into the center (pistils) of the same flower.

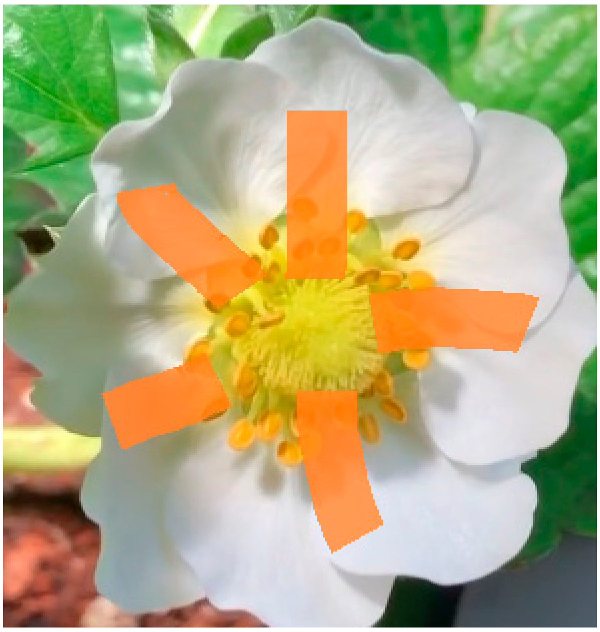


Figure S20. In practice, growers use a paintbrush to brush the outer edge of the flower to move pollen into the center from five directions with a result that pollination distribution is uneven.

Table S8. The strawberry information we collected under two pollination conditions (10 for each)

Pollination	Achene number	Fruit weight	Achene distribution
Artificial	311 ± 6.34a	17.51 ± 0.32a	uneven
Bee	265 ± 9.21a	14.75 ±0.46a	even

Means ± standard error (n=10) within each column followed by the same letter are not significantly different (P>0.05)

Part 12. Planting patterns

Figure S21. Diverse hive locations in experiment 2. Green dots represent the strawberry plants and the purple dot represents the bee hive.

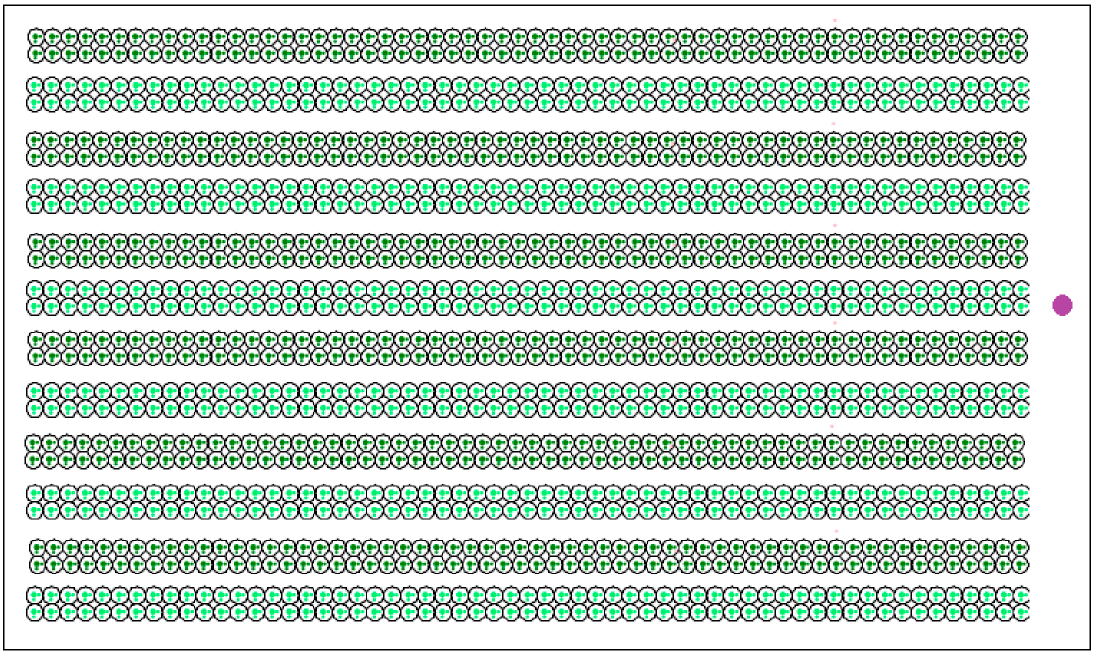


Figure S22. Different cultivars were planted in the interval beds in experiment 3.

Part 13. Bee foraging

During bloom, bees search and visit flowers in optimal time according to Table 3 to obtain pollen grains. Bee foraging activity is defined as the repeated transitions between three states: [stay nest, search flower and visit flower].

(1) **Stay nest**: When bloom begins, bees check weather conditions before starting foraging from their nests. The bee is assigned a workload comprised of the number of stems it will visit in this foraging.

(2) **Search flower**: When a honey bee leaves its hive and starts searching for flowers, it first checks its memory to find the rewarding flower that has been remembered since the last foraging bout. Bees tend to fly to the same floral sources as long as it remains profitable. If the information of rewarding flower exists, it flies to an area that contains that flower. If the memory is empty, it starts non-stop random searches until the nearby inflorescence in bloom is found. The random search is performed in each simulation step as a movement from one position to another that is determined by flight speed and heading. Bees can achieve a tradeoff

between efficiency and accuracy, i.e., they fly slower in area when flowers with rewards occur compared to empty space. Therefore, it is reasonable to use an adaptive searching strategy in which flight speed related to search of floral rewards is a nonlinear function of the number of failed searches:

flight searching speed = max(max_speed * (1-exp (- failed_searches)), min_speed)

The failed search is defined as the accumulative times of failure in locating blooming flowers after multiple consecutive movements; the *max speed* and the *min_speed* are parameters that define the bounds of flight speed. Once a blooming flower is located, the failed searches become 0, i.e., the bee stops searching (flight speed = *min_speed*); and with the increase of failed searches, the searching speed dramatically approaches the maximum speed. The criterion of finding a target inflorescence to visit is that at least one flower in bloom on a inflorescence appears to the bee's perceptive zone (a circle with radius of 1.1m around the bee). If more than one inflorescence meet the criterion, the bee choose the closest one that has not been visited recently as its target stem to investigate.

(3) **Visit flower**: Once a target inflorescence is located, the bee visits all flowers on it. Then the bee randomly chooses a flower on the inflorescence to land on and finishes the following visiting procedures before the bee moves to the other flowers on the same inflorescence: Deposit pollen grains on to flower stigma. The number of deposited pollen grains for a honeybee per visit is set to 30; Extracted pollen grains from the anthers. The number of pollen grains removed per visit is about 9000.

Once flower visits on one inflorescence are completed, the bee memorizes the inflorescence as the most recent memory and forgets the oldest inflorescence.

During foraging, if the bee has collected enough pollen grains and if its accumulated flight distance since the beginning of the same foraging bout while keeping beyond its foraging range, it returns to its hive immediately, unloads pollen grains from its pollen body capacity and decides whether to start a new foraging bout depending upon the time of day and the weather conditions.

Part 14. Model main parameters in simulation

(1) Greenhouse

Parameter	Default value	Remarks
LANDSCAPE_SIZE_LENTH	80m or 60m	Length of the greenhouse
LANDSCAPE_SIZE_WIDTH	8m	Width of the greenhouse
nb_clones_column	390	The strawberry number in a row
nb_clones_row	12	The row number in the greenhouse
distance_beds	0.40m	Distance between beds
max_temperature	set by users	The max temperature in a simulation day
min_temperature	set by users	The max temperature in a simulation day
simulation_duration	120 days	Simulation duration in an experiment

(2) Strawberry

Parameter	Default value	Remarks
ovules_in_first_inflorescence	350	Ovules number of the flowers in primary inflorescences
vules_in_second_inflorescence	260	Ovules number of the flowers in secondary inflorescences

T_base_strawberry_for_bloom	0 ℃	The base temperature for strawberry bloom
mean_gdd_primary	586 ℃	Average GDD required for flowering in primary inflorescences
mean_gdd_secondary	1066 ℃	Average GDD required for flowering in secondary inflorescences
sd_gdd	120	GDD variance for strawberry bloom
T_base_strawberry_for_ripeness	6 ℃	The base temperature for berry growth
days_strawberry_bloom	5 days	The flowering duration of strawberries
strawberry_self_ compatibility_probability	80%	Strawberry self-compatibility probability
inflorescence_position	1 or 2	1: primary inflorescence 2: secondary inflorescence
nb_flowers_in_inflorescence	See Table 1	The number of flowers in the inflorescence.

(3) Bees

Parameter	Default value	Remarks
memory_length	5	the number of visited inflorescences that a bee can remember
max_pollen_load	500,000	The maximum number of pollen grains carried by a bee
nb_honybee_on_hive	8,000	Bee number in the hive
ratio_bee_worker	40%	The proportion of worker bees in a hive
honeybee_activity_ratio	See Table 3	The proportion of bees leaving the nest on different hours
honeybee_workload	14	The max number of inflorescences visited by a bee when foraging
honeybee_max_travel_dist	1,000m	Maximum flying distance of a bees when foraging in a greenhouse
honeybee_pollen_extracted_per_visit	9,000	The number of pollen grains removed per visit by a bee
nb_pollen_deposited_per_visit	30	The number of deposited pollen grains per visit by a

		bee
bee_state	0	0: Stay nest 1: Search flower 2: Visit flower
max_speed	5.1 m/s	Max flight speed of a bee in the greenhouse
min_speed	0.1 m/s	minimum flight speed of a bee in the greenhouse
foraging_temperature_Lbound	30 ℃	The maximum bound for bee foraging
foraging_temperature_Ubound	15 ℃	The minimum bound for bee foraging