Spinach Crop Diversity: Modeling the Spread of Downy Mildew

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1 Introduction

Downy mildew is a disease that has plagued spinach populations worldwide for decades, and this project aims to create a mathematical model that provides a design plan for diverse spinach populations to minimize crop loss that has resulted from downy mildew.
As more research has been done in this field, it has become increasingly apparent that "lower efficacy of resistance crops generally leads to greater reliance on chemical pesticides, with potential negative impacts on non agricultural ecosystems", which is often referred to as spatial diversification. This is a growing area of concern that farmers are trying to avoid, as more information comes out about the negative side effects of chemical involvement in natural growth. Due to the growing concern in this area, the importance of spatial arrangement of a variety of species of spinach has become prevalent in this field [3].
For this project, there are 18 species of spinach and 19 races of Downy Mildew that are being considered [2]. Through the development and application of epidemiological models, this project will help farmers to become more knowledgeable about the positive effect spatial arrangement and multiple cultivar mixes can have on crop yield.

2 Mathematical Model

2.1 Choosing a SIR Model

To model the spread of downy mildew (DM) in spinach populations, the most thorough way to do so was through adapting a SIR model. The "S" is our susceptible group, which is any plant that has no resistance to the race of DM present and has not been infected yet. The "I" indicates the group of plants that have become infected with DM, and the "R" group means that the spinach plant has died and has been physically removed from the crop by a farmer.
There are many components to how DM spreads in a spinach crop, such as current weather conditions, time of year, wind speed, and human error. With all of the elements that contribute to the spread of this pathogen, we chose an SIR model because we could manipulate certain parameters to model how changing these external components affect crop loss [1].

From the data gathered at Johnny Seeds, we were able to get an idea of which species are resistant to which races of DM. This element is also factored into the scenarios mentioned later, as the goal is to arrange plants in a conscious manner to minimize crop loss [3].

3 Methods

3.1 Assumptions

For our model, we selected the Sunangel and Tundra species of spinach because they both mature in 27 days, are ready for harvest in spring or fall, and germinate best in 85°F. Sunangel is resistant to all 19 races of DM except for race 10, while Tundra is resistant to all but race 14, 17, and 19 of DM. To reduce complexities in our model, we assume only one race of DM can be present at a time, which we chose to be DM race 10 because Sunangel is susceptible to it while Tundra is resistant [2]. It is also important to note that for our model, it is assumed that a resistant plant has 100% resistance.

3.2 Qualitative Methods

We designed 3 scenarios to model the spread of DM: no crop diversity, medium diversity, and maximum diversity. Each scenario is constructed as a 10 by 10 crop with ten initially infectious plants that are randomly selected.

3.2.1 Scenario 1

Scenario 1 is reflective of a monocrop of Sunangel, in which there is no diversity. This means that all spinach plants are susceptible to DM race 10. Figure 1 displays this scenario in which the diameter is equal to 1, which influences how quickly DM can spread within a crop. Figure 2 displays the same monocrop of Sunangel and DM race 10, now with a diameter of 2, which increases the interaction between plants [2].

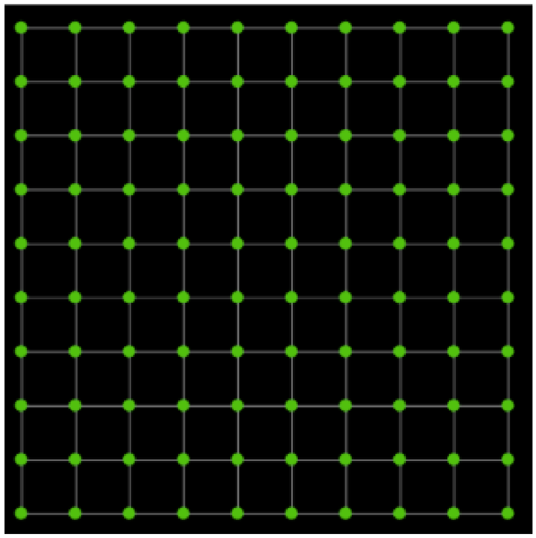

Figure 1: D=1

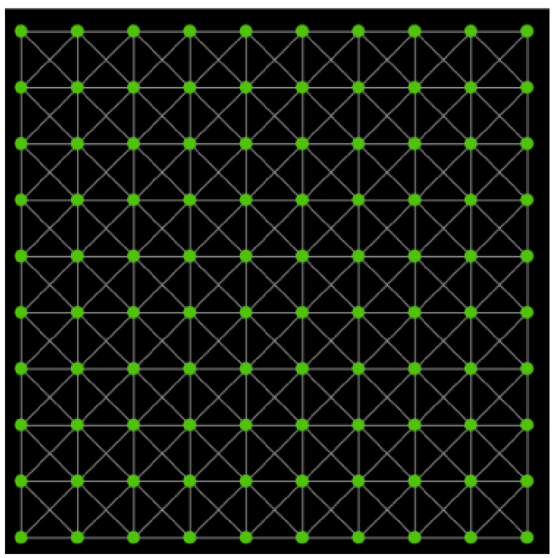

Figure 2: D=2

3.2.2 Scenario 2

Scenario 2 is reflective of medium diversity, in which both Sunangel and Tundra spinach species are planted in a crop. Figure 3 displays the crop pattern when the diameter is 1, in which four of the same species are planted in a group, and each row alternates between the Sunangel and Tundra group. Sunangel is susceptible to DM race 10, which is represented by the green dots. Tundra is resistant to DM race 10, which is represented by the gray dots. Figure 4 shows this case when the diameter increases to 2 [2].

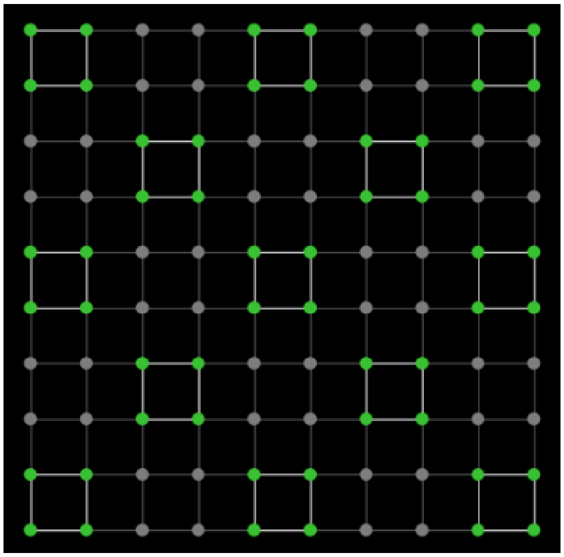

Figure 3: D=1

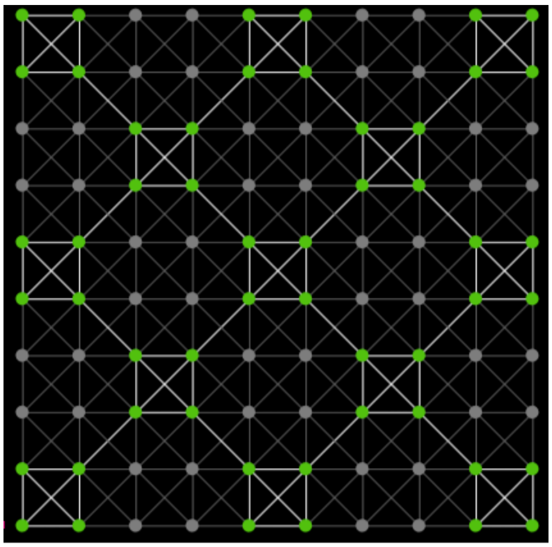

Figure 4: D=2

3.2.3 Scenario 3

Scenario 3 is reflective of maximum diversity between Sunangel and Tundra. Each individual spinach plant alternates between susceptible and resistant to DM race 10 in each row and column of this crop. Like scenario 2, the green dots represent the susceptible plant (Sunangel) and the gray dots represent the resistant plant (Tundra). Figure 5 shows the case when the diameter is equal to 1, and Figure 6 shows the case when the diameter is equal to 2.

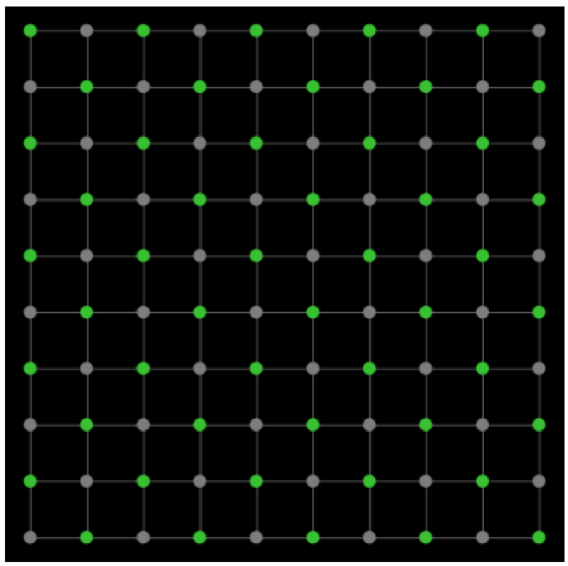

Figure 5: D=1

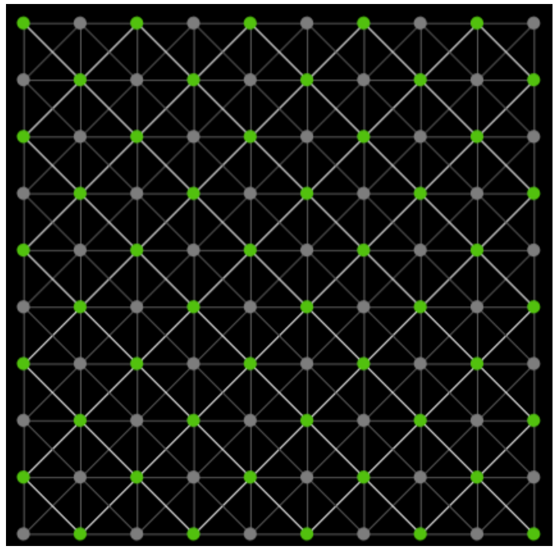

Figure 6: D=2

3.3 Numerical Methods

We use Netlogo to run each scenario to produce a spreadsheet of the calculated data. Our two parameters of interest are the number of time steps it takes until the disease terminates and the number of spinach plants that die from the disease. For each of these parameters, we calculate the mean and standard deviation.

4 Results

4.1 Parameter Estimation

4.1.1 Infection Probability

With the many ways that DM spreads, we chose to model three different infection probabilities to imitate how different resistances and their interactions with different spinach types would look like in a plot. For the three infection probabilities, we chose the values: 99%, 50%, 1%. The first value, 99%, is a maximum infection scenario, which incorporates factors such as high wind speeds, human error, and ideal conditions for DM spread. The second value, 50%, models a medium infection scenario, where the external conditions that amplify DM spread are not as intense and do not impact the plot of spinach as severely. The last scenario with an infection probability of 1% indicates minimal ability for DM to spread, meaning the external conditions have nearly zero influence on the plot of DM.

4.1.2 End Infection Probability

End infection probability in this model is the measure of how fast a removed crop is removed from the plot before it can infect other plants. This adaptation of the typical removed definition accounts for the characteristic of DM where a dead plant can continue to infect plants even after the plant is dead. For this, we chose two parameter values: 5%, 100%. The first value, 50%, represents the situation where a farmer is not as diligent as they should be in the removal of DM. In mathematical terms, there is a 50% chance that the infected spinach plant will infect other plants in the specified radius before the plant can be removed. However, the second value, 100%, represents the highest possible diligence by a farmer to remove a plant before the surrounding plants are infected.

4.1.3 Exclusion of a Latent Period

For our model, we chose not to have a latent period because of the rapid ability of DM to infect and kill a plant of spinach. The latent period would have told us there was a specific amount of time whether the plant becomes infected after being exposed, but DM has such a high transmission rate that we decided to omit this component from our model.

4.2 Sensitivity Analysis

4.2.1 Changing the value of D

Changing the infection radius or D resulted in change in all of the key values we considered. These being: mean duration, standard deviation of ticks, mean number of removed plants, and the standard deviation of removed plants. There are six combinations of infection probability and end infection probability that we considered. The combinations are as follows: $(.99, .5), (.99, 1), (.5, .5), (.5, 1), (.001, .5)$, and $(.001, 1)$. For scenario 1, changing D resulted in an increase in mean duration values for all combinations of infection probability/end infection probability except for one combination. This combination was an infection probability of .001 and an end infection

probability of 1. The standard deviation of ticks was the same for all combinations. Increasing D from 1 to 2 caused an increase in the standard deviation of ticks. The mean removed values for the first two combinations of infection probability and end infection probability did not change. The combination of .5 and .5 lead to a slight increase in the mean duration. Increasing D caused a decrease in the mean removed for the rest of the combinations. Increasing D also resulted in a decrease in the standard deviation of removed plants.
For scenario 2, the increase in D from 1 to 2 caused an increase in the mean duration for the first four combinations. The mean duration for the last two combinations got smaller after the change in D. Like in scenario 1, the standard deviation of ticks was the same for all combinations. The increase in D resulted in an increase in the standard deviation. While the mean removed for the first five combinations increased after D moved from 1 to 2, the mean removed decreased for the last combination. The standard deviation of removed plants was the same value for all combinations. Changing D from 1 to 2 caused an increase in this value.
Scenario 3 followed a different pattern from what we observed in the other scenarios. The mean duration decreased for the first five combinations and increased for the last combination when D was changed to 2. The standard deviation decreased for all combinations when D was increased. More plants were removed on average for 5 of the 6 combinations when D was 2. The standard deviation of removed plants decreased for all combinations.

5 Discussion

After calculating the mean and standard deviation of both the number of dead (removed) spinach plants and duration of disease period, we examined our data to determine the "best" scenario for each parameter combination. Here, we define the "best" scenario to be the scenario with the minimum amount of dead spinach plants or duration of the disease. We determined the best scenario for each parameter combination of infection probability (IP) and end infection probability (EP).

5.1 D=1

5.1.1 Best Survival Rate

Table 1 and Figure 7 display our results for mean dead plants when D = 1. Both clearly show that scenario 1 is the worst scenario for all cases because scenario 1 has the maximum number of dead plants for each parameter combination. When the IP is high (50% or greater), scenario 2 is the best scenario because it has the minimum amount of dead plants, thus a higher survival rate of susceptible plants. Scenario 3 is the best scenario when IP is 1%, but it is also important to note that the variance between all scenarios decreases as IP decreases.

5.1.2 Result from Farmer Diligence

When the EP (diligence of the farmer to physically remove infectious dead plants) changes from 50% to 100% in Table 1, there is little change in the mean number of dead plants. Although the EP doesn't appear to have major significance on mean number of dead plants, it should be noted that the mean number of dead plants changes the most when EP changes from 50% to 100% and IP is 50%.

Mean Dead Plants D = 1	IP = 99% EP = 50%	IP = 99% EP = 100%	IP = 50% EP = 50%	IP = 50% EP = 100%	IP = 1% EP = 50%	IP = 1% EP = 100%
Scenario 1	100	100	96.06	80.45	10.68	10.36
Scenario 2	35.97	36	29.53	23.72	10.39	10.23
Scenario 3	49.96	50	43.48	33.52	8.44	8.15
Best Scenario	**2**	**2**	**2**	**2**	**3**	**3**

Table 1

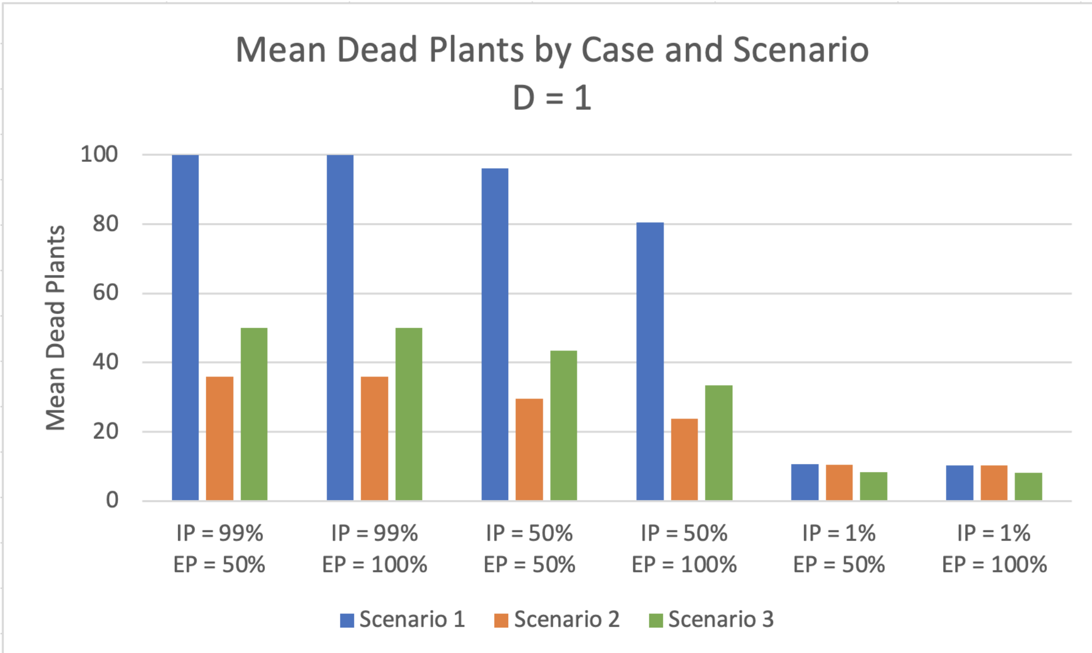

Figure 7

5.1.3 Length of Disease Period and Farmer Diligence

Moreover, the diligence of the farmer appears to have more of an association with the mean duration of the disease period rather than number of mean dead plants. Table 2 and Figure 8 show that when EP increases from 50% to 100%, the mean duration significantly decreases for all three scenarios. It is likely that the more diligent the farmer is, the shorter the disease period becomes. It also seems that changing the EP has more of an influence on the duration of the disease period than changing the IP.

Mean Duration D = 1	IP = 99% EP = 50%	IP = 99% EP = 100%	IP = 50% EP = 50%	IP = 50% EP = 100%	IP = 1% EP = 50%	IP = 1% EP = 100%
Scenario 1	9.98	5	12.79	9	5.02	1.29
Scenario 2	7.51	3.15	8.24	3.7	4.94	1.23
Scenario 3	9.53	6	12.1	6.89	4.79	1.15
Best Scenario	**2**	**2**	**2**	**2**	**3**	**3**

Table 2

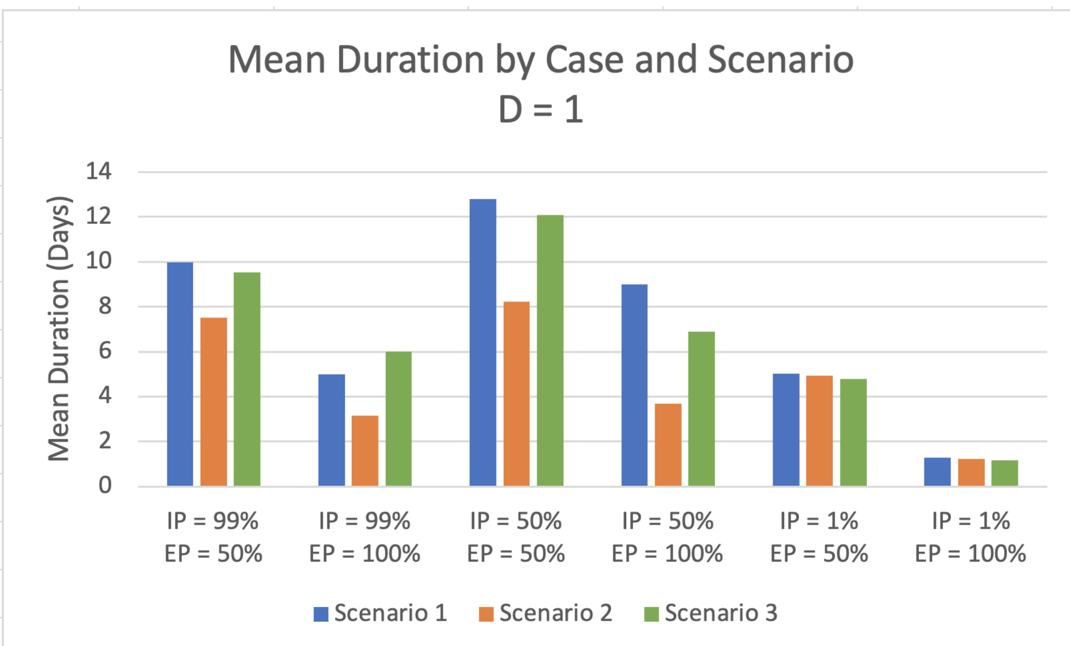

Figure 8

5.2 D=2

5.2.1 Best Survival Rate

Table 3 and Figure 9 show that, despite increasing D from 1 to 2, scenario 1 remains the worst scenario for all cases because it contains the maximum amount of dead plants. When IP is 99%, scenario 3 is the best scenario. When infection probability is 50%, scenario 2 is the best scenario. When IP is 1% and EP is 50%, scenario 3 is the best scenario. When IP is 1% and EP is 100%, scenario 2 is the best scenario. When D = 2, it is important to notice the narrow range of values for scenario 2 and 3 for all parameter combinations in Table 3. This narrow range makes it unsurprising that scenario 2 and 3 make good crop candidates when D = 2.

Mean Dead Plants D = 2	IP = 99% EP = 50%	IP = 99% EP = 100%	IP = 50% EP = 50%	IP = 50% EP = 100%	IP = 1% EP = 50%	IP = 1% EP = 100%
Scenario 1	100	100	100	76.97	10.59	10.29
Scenario 2	51.96	52	45.48	35.52	10.44	10.15
Scenario 3	50	49.98	46.01	38.95	10.43	10.25
Best Scenario	**3**	**3**	**2**	**2**	**3**	**2**

Table 3

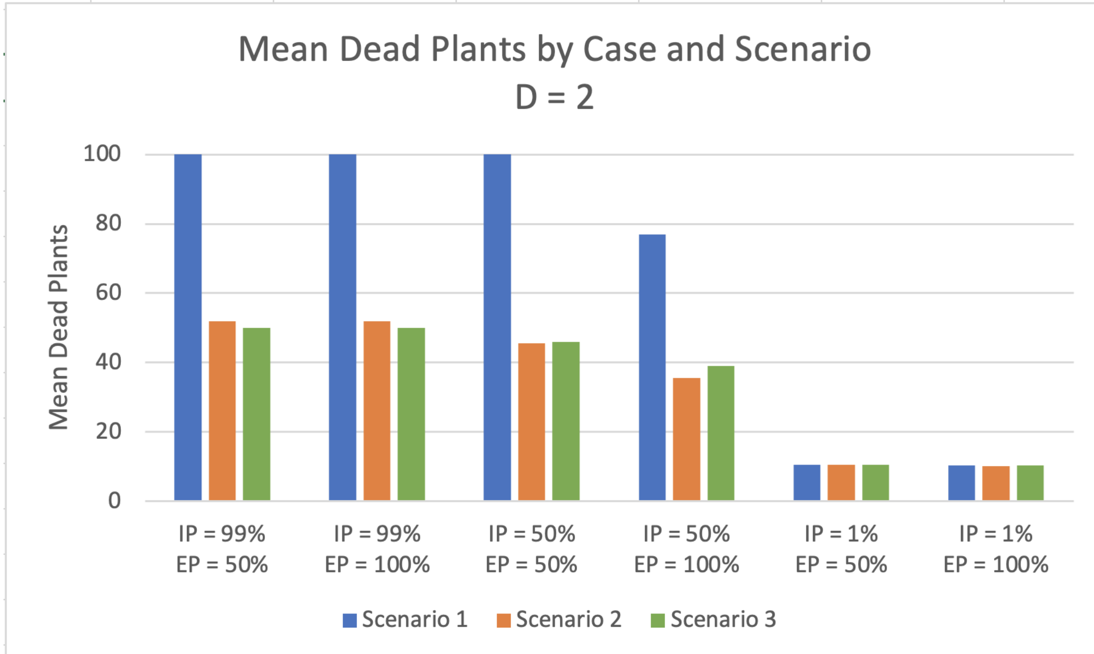

Figure 9

5.2.2 Result from Farmer Diligence

Similar to D = 1, when the EP changes from 50% to 100% in Table 3, there is little change in the mean number of dead plants. The most change occurs, again, when the EP changes from 50% to 100% and IP is 50%. Changing the IP appears to have more of an influence on the number of mean dead plants than changing the EP.

5.2.3 Length of Disease Period and Farmer Diligence

Similarly to D = 1 results, the diligence of the farmer appears to have an influence on the mean duration of the disease period. Table 4 and Figure 10 show that when the EP increases from (50%) to (100%), the mean duration significantly decreases. Again, it is likely that the more diligent the farmer is, the shorter the disease period becomes. It is also important to note again that changing the EP has more of an influence on the duration of the disease period than changing the IP.

Mean Duration D = 2	IP = 99% EP = 50%	IP = 99% EP = 100%	IP = 50% EP = 50%	IP = 50% EP = 100%	IP = 1% EP = 50%	IP = 1% EP = 100%
Scenario 1	10.6	10.6	12.89	10.57	5.08	1.25
Scenario 2	9.53	6	12.1	6.89	4.79	1.15
Scenario 3	8.8	4.99	10.45	6.04	4.97	1.24
Best Scenario	**3**	**3**	**3**	**3**	**2**	**2**

Table 4

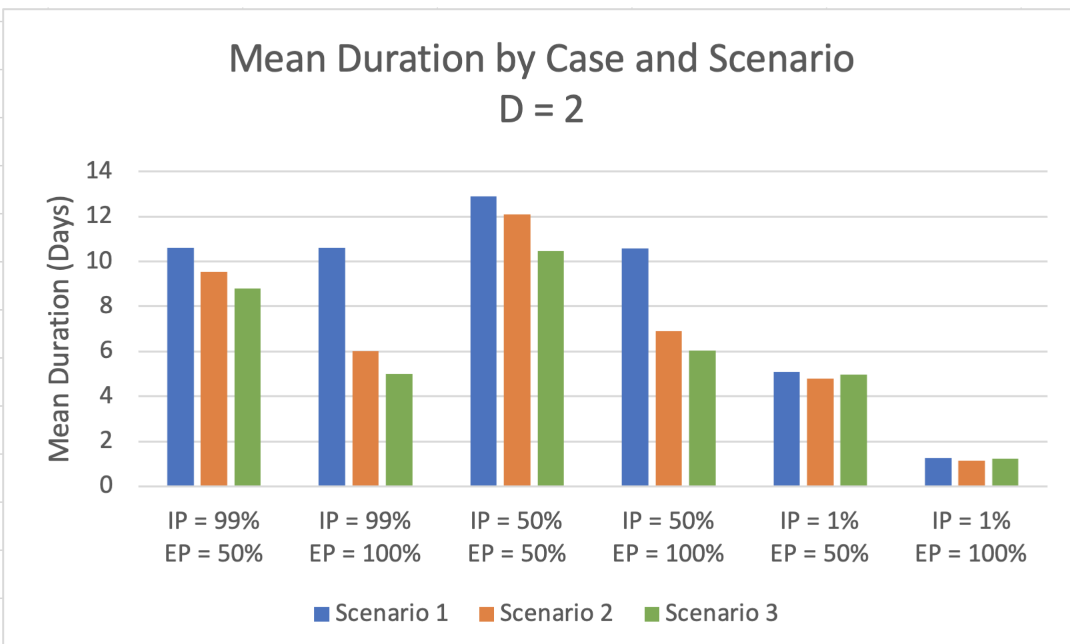

Figure 10

5.3 Conclusions

Considering each scenario and each parameter combination for each diameter, it is clear that scenario 1 (no crop diversity) is the worst scenario. We also found that changing the values of IP has the most influence on the mean number of dead plants, while changing the value of EP has the most influence on the mean duration of the disease period. Incorporating some sort of crop diversity of spinach species with varying resistances to DM races appears to be beneficial to farmers in order to minimize disease spread.

5.3.1 D = 1

To minimize the mean number of dead plants when the diameter of infection is 1, scenario 2 is the best scenario because it produces the minimal number of plants for the most parameter combinations. To minimize the mean duration of the disease period, scenario 2 is the best scenario because it also produces the minimal number of days for the most parameter combinations.

5.3.2 D = 2

To minimize the mean number of dead plants when the diameter of infection is 2, the best scenario is both scenario 2 and 3 because there is such low variance between the values of each scenario for all parameter combinations. To minimize the mean duration of the disease period, scenario 3 is the best scenario because it also produces the minimal number of days for the most parameter combinations.

5.4 Future Work

5.4.1 Increase Number of Species

In our models, we only accounted for the plot of spinach having two species of spinach and how the two interacted with one another. However, in many large scale spinach plots, it is important to expand this number to account for interactions between three or more plants. With more time, we would look at introducing another species into our plot, with different resistances from the already existing other species, and see if arrangements of multiple types of spinach would be ever more beneficial to fighting crop loss than the arrangement of only two.

5.4.2 Higher Values of D

As mentioned previously, the value for d indicates the infection radius, and the max value we had input was two. With the model we chose, we could only input integer values for d, but increasing that d to three or higher would increase the radius of infection in the plot. This increase could give evidence about trends that occur in these plots when conditions encourage DM growth, high wind speeds, and extremely high human error.

5.4.3 Inclusion of a Latent Period

With Spinach DM, the latency period is hard to incorporate without making a broad assumption that a plant can come into contact with a spore and not become infected. This assumption is wrong, and making it would invalidate the results we are trying to present. However, if we wanted to work with a latent period, we could look into other plants that fall victim to DM which include corn, grapes, and more common vegetables. Their fragility is not as high as that of spinach, which would give us the ability to examine how latency impacts crop loss.

6 Acknowledgments

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References

[1] Choudhury, R A et al. “Season-Long Dynamics of Spinach Downy Mildew Determined by Spore Trapping and Disease Incidence.” *Phytopathology* vol. 106,11 (2016): 1311-1318. doi:10.1094/PHYTO-12-15-0333-R

[2] ”Space Smooth-Leaf Spinach.”. *Johnny’s Selected Seeds* https://www.johnnyseeds.com/vegetables/spinach/.

[3] Watkinson-Powell, Benjamin et al. “When Does Spatial Diversification Usefully Maximize the Durability of Crop Disease Resistance?.” *Phytopathology* vol. 110,11 (2020): 1808-1820. doi:10.1094/PHYTO-07-19-0261-R