Project title:	*MILIONCAST* development *for hosting on* CropMonitor Pro *website*
Project number:	
Project leader:	Femke van den Berg, Fera Science Ltd.
Report:	Final report, August 2019
Previous report:	N/A
Key staff:	Femke van den Berg Marc Kennedy
Location of project:	Sand Hutton, York
Industry Representative:	
Date project commenced:	03 June 2019

DISCLAIMER

The results and conclusions in this report are based on an investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

Femke van den Berg

Senior Scientist

Fera Science Ltd.

Signature ....   Date .....08/08/2019..........

[Name]

[Position]

[Organisation]

Signature ....   Date ....

Report authorised by:

[Name]

[Position]

[Organisation]

Signature ....   Date ....

[Name]

[Position]

[Organisation]

Signature ....   Date ....

CONTENTS

GROWER SUMMARY

Headline

The MILIONCAST model was connected to the CropMonitor platform and now provides free access to regional risk predictions of onion downy mildew for fifteen regions in England and Wales (www.cropmonitor.co.uk). The CropMonitor Pro subscription service will provide local risk predictions (based on the closest 2x2 km weather grid) which can assist in rationalising the use of fungicide treatments.

Model performance was tested using both spore presence and symptom presence data from a limited number of growers. Further validation through grower's feedback on use of the new system is recommended to facilitate further model improvements and fully evaluate potential grower benefits.

Background

The MILIONCAST forecast model which is used to identify periods of high infection risk for downy mildew on onion is frequently used and well respected by onion growers. The current software is however outdated and increasingly harder to use due to version incompatibility. There was therefore an urgent need to make the MILIONCAST forecast model available on a sustainable and easy to use platform.

Summary

Downy mildew (*Peronospora destructor*) is a common disease that can result in major yield losses in bulb and salad onions and in onion seed production (Develash and Sugha, 1997) and crops may receive fungicide treatments as frequently as every 10 days. A decision support system which automatically calculates the risk of infection, could help growers to better time fungicide applications leading to earlier and more efficient disease control. Gilles *et al*. (2004) developed algorithms into a forecast model known as MILIONCAST which predicts i) sporulation, ii) infection and iii) latent period development with subsequent symptom expression. Since their development the MILIONCAST algorithms have been successfully used by growers to guide fungicide applications for downy mildew on onions. The software used to run the algorithms is however outdated and there was a need to host MILIONCAST on a more sustainable platform.

The CropMonitor Pro platform developed by Fera Science Ltd on behalf of the Crop Health and Protection Centre provides infection risk predictions for a large range of pests and diseases affecting wheat and oilseed rape crops (www.cropmonitor.co.uk). This platform uses automated weather feeds and requires very limited user input. The platform has been built in a generic manner allowing it to be easily expanded to include new crop diseases or pests. The main aim of this project was to host the MILIONCAST algorithms as extracted by AHDB on the CropMonitor platform.

This platform now provides regional risk predictions for downy mildew on onions (free of charge) and allows growers to register to the crop-specific subscription service (within CropMonitor Pro) which gives access to local risk predictions (for the closest 2x2 km weather grid).

A previous validation performed by Gilles *et al.* (2004) between 1996 and 2001 showed that spore production events were predicted with 81% accuracy and that the error on the latent period model was 1.9 days on average. However, the authors stated that overall model performance in which all model components (sporulation, infection and latent period) were combined was relatively low (61 % of sporulation/ infection events were associated with observed peaks in disease increase). Then again, this is still a significant improvement compared to random predictions (56%; $P < 0.001$). Our validation shows similar trends, although the data available for validation were very limited. In the sporulation validation within this study we found a clear correlation between the score on the lateral flow device (LFD) used for testing spore presence in air samples and the predicted sporulation risk score from the model. The LFD device is however still under development and needs to be fully calibrated before final conclusions are drawn based on these results and the LFD needs to be tested against a much greater number of samples before it can be concluded whether the observed correlation is significant or not.

Although the overall model performance might not be very high it is promising that the sporulation model is performing well. Disease control is most effective when targeted at the time of first infection rather than when symptoms are clearly visible within the crop. It would therefore be very valuable to do a detailed analysis of the model's capability to predict the first infection event by comparing predicted dates of first infection with the date on which the disease could first be detected in its latent state within the crop (i.e. before symptom expression). This would require in-field diagnostic testing of the leaves.

The CropMonitor Pro platform also includes a surveillance platform which allows and encourages subscribers to submit dates of observation of first symptoms within the registered fields or on the wider farm. These data could be used for continued further validation of the model's capability to predict first symptoms within a field.

Financial Benefits

Due to the limited data available to estimate the accuracy of the model prediction it is difficult to give an indication of potential financial benefits at this point. However, if the model proves able to guide the grower to more accurately time fungicide applications this will result in more effective control and hence increased yield and potentially a reduction in the total number of fungicide applications required within a season.

Action Points

When logging in to the CropMonitor Pro services for onion downy mildew growers are encouraged to submit regular data on whether the disease has been observed within the registered field and/or on the wider farm within the ‘My sightings’ section as these data can be used for further model validation.

SCIENCE SECTION

Introduction

Downy mildew (*Peronospora destructor*) is a common disease that can result in major yield losses in bulb and salad onions and in onion seed production (Develash and Sugha, 1997). Significant downy mildew infections in bulb onion crops can cause early defoliation, reduced bulb sizes, and poor storage quality of bulbs. As a result, onion crops may receive fungicide treatments as frequently as every 10 days. To reduce the impact of disease control treatments on the environment and limit fungicide resistance development it is crucial that fungicides are accurately timed and only applied when conditions are favourable for disease development.

Onion downy mildew spores are wind dispersed from infected onion bulbs left in the field or in cull piles. Additionally, sexual spores may persist in the soil and can pose a risk of infection during the next season. Spore production is optimal during nights with a high humidity and moderate temperature. Large numbers of spores are thought to be correlated with disease spread within the crop (Gilles *et al.*, 2004). A decision support system which automatically calculates the risk of infection, could help growers to better time fungicide applications leading to earlier and more efficient disease control.

Gilles *et al*. (2004) developed algorithms into a forecast model known as MILIONCAST which predict i) sporulation, ii) infection and iii) latent period development with subsequent symptom expression. Since their development the MILIONCAST algorithms have been successfully used by growers to guide fungicide applications for downy mildew on onions. The software used to run the algorithms is however outdated and requires a significant amount of user input. In particular, it requires the user to supply their own weather data.

The CropMonitor Pro platform developed by Fera Science Ltd on behalf of the Crop Health and Protection Centre provides infection risk predictions for a large range of pests and diseases affecting wheat and oilseed rape crops (www.cropmonitor.co.uk). This platform uses automated weather feeds and requires limited to no user input. The platform has been built in a generic manner allowing it to be easily expanded to include new crop diseases or pests. The main aim of this project was to host the MILIONCAST algorithms as extracted by AHDB on the CropMonitor Pro platform in order that it will be sustainable for the future and receive ongoing maintenance.

As part of the onion downy mildew services, regional disease risk predictions (15 regions) will be available free of charge, whereas local predictions will be available under a subscription service only (CropMonitor Pro). CropMonitor Pro now uses 2x2 km gridded weather data, which means that we can provide predictions across the whole of England and Wales. Once

MILIONCAST is available on CropMonitor Pro it becomes part of the subscription service. A beta-validation version of this service is now available for wheat at www.cropmonitor.co.uk. The main aims of the project were:

- Connect the MILIONCAST model to the CropMonitor platform
- Provide regional risk predictions available free of charge
- Provide local risk predictions (for the closest 2x2 km grid) available under the subscription service
- Perform a validation of the model predictions versus disease observation data provided via AHDB

Materials and methods

Implementation of the MILIONCAST model

Based on information provided by AHDB (Appendix A) together with some additional information from the literature, a new implementation of the MILIONCAST model has been created and is now being hosted within the CropMonitor platform. Required modifications and new model features are documented in the next few paragraphs.

Modifications required

Sporulation. The original sporulation algorithm (Appendix A) presumes a time step of half an hour. Within the CropMonitor Pro system weather data are only available on an hourly basis and hence we have generalised the algorithm to work with hourly rather than 30 minute intervals.

When testing which overnight periods to include, humidity >= 92 is used instead of humidity > 92. This is a minor adjustment but will allow for readings where the true reading is greater than 92 but due to rounding has been recorded as 92.

The parameters listed in Appendix A do not match the parameterisation used in the code, despite appearing to match the parameterisation used in Gilles and Kennedy (2004). Note that in Appendix A betaC is listed twice with different values, whereas gammaC is missing, so a typo is assumed here. The values were checked against the original source equations and the corrected values are listed below.

The sporulation algorithm is hence summarised as follows:

```
For each reading from noon to 17:30

        inhib += airTemp

mcon01 = 0.0
```



```
cumSpor = 0.0

for each reading

        if (between sunset and 9:00am) && humidity >= 92

                mcon01 += 1

                conC = gammaDist(alphaC, betaC, gammaC, airTemp)

                conCPrime = conC / log10(exp(1.0))

                conM = 1.0 / gammaDist(alphaM, betaM, gammaM, airTemp)

                conRHDeter = pow((1.0 - r), (100.0 - humidity))

                conRate = (b * conCPrime * exp(exp(-exp(-b * (mcon01 -conM))) * conCPrime - exp(-b *
  (mcon01 - conM)) - b * (mcon01 - conM))) / 1

                cumSpor += (conRate * conRHDeter)

if inhib >= 386.7

cumSpor = 0.0

SC = log10(cumSpor + 1.0)
```

With $gammaDist(\alpha,\beta,\gamma,T) = \frac{\gamma T^{\beta-1} e^{-T/\alpha}}{a^{\beta}\Gamma(\beta)}$ and whereby, $\alpha_C = 11.95$; $\beta_C = 2.15$; $\gamma_C = 212.92$; $\alpha_M = 6.926$; $\beta_M = 2.614$; $\gamma_M = 4.0138$; b = 0.903; r = 0.3968; $\alpha_L = 4.92$; $\beta_L = 5.69$; $\gamma_C = 3.479$.

Infection. In the Infection model a threshold of 400 mV is used as a leaf wetness threshold. This value is dependent on the particular leaf wetness sensor setup and hence within the CropMonitor Pro system this has been replaced with a binary value designed to indicate whether a leaf is likely to be wet (Y=1/N=0). This uses a bespoke leaf wetness model within the CropMonitor Pro platform.

The infection algorithm is hence summarised as follows:

```
if leaf wetness = 1

mcon04 = 1.0 / (2.0 * (20.26 - 1.801 * airTemp + 0.0682 * airTemp * airTemp)

else

        mcon04 = 0.0

mcon05[0] = mcon04
```



```
mcon06[0]= mcon05[0]

foreach record starting at the second

if leaf wetness = 1

mcon04 = 1.0 / (2.0 * (20.26 – 1.801 * airTemp + 0.0682 * airTemp * airTemp)

else

                mcon04 = 0.0

        mcon05[i] = mcon05[i-1] + mcon04

        if mcon05[i] == mcon05[i – 1]

                mcon06[i] = mcon05[i]

        else

                mcon06[i] = mcon06[i -1]

        IP[i] = mcon05[i] – mcon06[i]
```

Latent period. In the Latent Period algorithm description, bullet 2 has been interpreted as follows: “An infection period starts after 09:00 on the sporulation day and [threshold exceeds 1] before 02:00 the next day. The latent period starts when the infection period starts”. In the code section the following interpretations have been made, which are consistent with the model as described in the literature:

1. T = airTemp
2. timestep = length of time covered by the record. Typically, this will have the value 1 (hour) or 0.5 (hours) but from reading Gilles and Kennedy (2004) this has been scaled to a day rate to match the model equations there. The resulting plots have the correct scaling.

Leaf wetness. The algorithms require a leaf wetness status at each time point. The leaf wetness data is predicted using the Fera bespoke leaf wetness algorithm based on relative humidity and temperature data. Seeing as leaf wetness is associated with an increased risk of infections, it is important for the leaf wetness model to result in a low number of false negative predictions. Table 1 summarises the model prediction accuracies and shows that a total of only 23.8 % of the true wet cases were incorrectly classed as dry based on the training data.

In future, we are looking to include leaf wetness data from within field weather stations, at which point the MILIONCAST model will use the weather station data, where available, or the leaf wetness algorithm for sites where no in-field leaf wetness measurements are available.

Table 1. Summary of prediction accuracy of the leaf wetness prediction model.

	Predicted Dry	**Predicted Wet**
Observed Dry	100896 (78.5%)	27711 (21.5%)
Observed Wet	***27858 (23.8%)***	89120 (76.2%)

Risk allocations

The MILIONCAST algorithms were further extended to provide the user with a daily view of the perceived risk of infection by downy mildew. The ambition of CropMonitor Pro is to provide early warnings of disease/pest development and hence the red/amber/green (RAG) status represent to risk of infection rather than the risk of symptom expression. The plots will however still inform the user as to the expected onset of symptoms.

A single day risk indicator will be generated, which has a single risk value (low, medium, or high) on each day. For the MILIONCAST model a day is taken to be the period 9am until 9am the following morning. Risk values will be generated for the previous 14 days, current day and 4 days ahead.

Infection is assumed to occur when both the sporulation risk score has exceeded 4.15 and the infection risk score has exceeded 1 (between 9 am and the 2 am on the following day). Note that the algorithms used by Gilles *et al*. (2004) assess likelihood of spore presence on a daily rather than an hourly basis. Under field conditions infection would not occur if spores were not present at the time that the infection conditions were suitable. However, the current algorithm does not allow for this detailed assessment, which means that the spore and infection condition functions are not sequential so that the spore threshold needs to have been exceeded before the infection threshold is being assessed. Because of this, you would never expect to see the spore threshold and the infection threshold both being exceeded within the same day but on different hours of the day which would have meant that the latent period line should not have started.

Based on this we define the following: if spores are predicted to be present and infection conditions are predicted to be optimal during any time on a given day, then the daily risk of infection is assumed to be high (R/Red); if one condition is met but not the other or the value for one of the criteria is missing then the daily risk of infection is assumed moderate (A/Amber); if both conditions are not met then the daily risk of infection is assumed to be low (G/Green). If the values for both criteria are missing, then the risk is also assumed as missing (i.e. no risk will be defined).

Model validation

Field data were received on the 23rd and 24th of July 2019 for 4 locations: Ripple, Chicksands, Wretham and Lackford. At these 4 locations disease assessments were made starting from mid-May / early June up to the 20th of July. The growers taking part in the model validation exercise submitted data for their registered locations on whether visual symptoms were observed or not. Additionally, at each site a Burkard cyclone air sampler was run (Burkard Manufacturing Co.). These cyclone air samplers operate at an air flow of 10 to 15 L air / min, whereby air particulates are trapped in a 1.5 ml microfuge tube. The aim was to then test the content of the microfuge tube for presence of sporangia of *P. destructor* on a weekly basis using a lateral flow device (LFD) for onion downy mildew (supplied by Mologic Ltd) (Wakeham, 2016; Kennedy, 2019). For each sample the growers would assign a spore presence risk score between 0 and 10 (or category between low and high) according to the score card depicted in Figure 1. A total of 40 spore samples were tested for downy mildew spore presence: 8 samples between 12/06/2019 and 01/07/2019 at Wretham; 1 sample on 08/07/2019 at Lackford; 3 samples between 08/07/2019 and 17/07/2019 at Chicksands and 28 samples between 12/05/2019 and 13/07/2019 at Ripple.

The four field data collection locations were registered on the CropMonitor Pro platform so that location-specific risk predictions could be generated for the model validation exercise. For each date on which an LFD test was carried out, or for which disease observation data were available, the model was run to determine the associated predicted risk scores.

Results

Example outputs

When the user navigates to http://dev.cropmonitor.web-int-dev02.csl.gov.uk/map and selects Onion - downy mildew from the right hand menu they will see a view such as the view represented in Figure 2A. This view is part of the regional CropMonitor service and will be accessible free of charge without the need to register. The regional boundaries for risk predictions indicate defined areas of the country which differ significantly in inherent disease risk. These have been previously defined by statistical analysis of data on incidence and severity of diseases collected in annual Defra surveys over the last 30 years or more.

Field specific risk outputs will be only available under the subscription service (CropMonitor Pro). Once a user has registered their field and has activated their account, they will see their registered fields appear on the map (Figure 2B). As an example, the 4 locations involved in the model validation field data collection have been registered. The location markers indicating individual field locations will be coloured according to the prevailing risk at that specific location on that day.

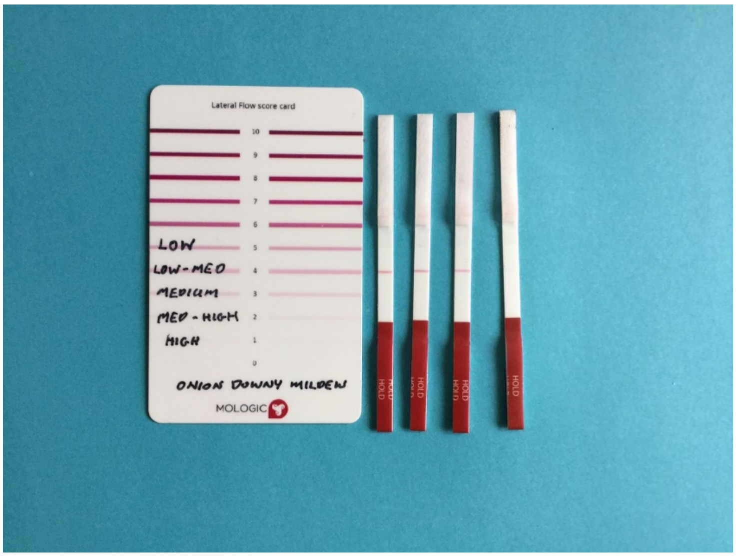

Figure 1. Lateral flow device and score card used for detection of downy mildew spore presence.

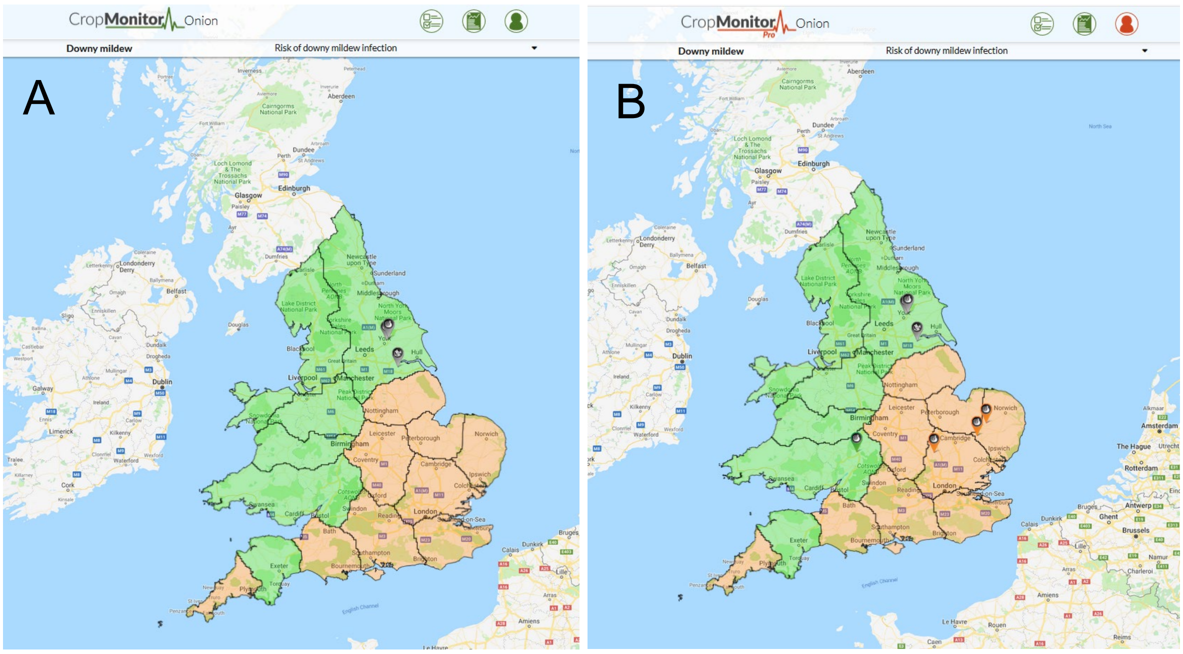

Figure 2. Regional view for (A) the free CropMonitor regional service and (B) the CropMonitor Pro subscription local service

Once logged in, the user can select one of their registered fields by clicking on a location marker to display the field-specific forecasts. An example output for 07/08/2019 at the Chicksands location is shown in Figure 3 with a zoomed view of the plot (plots can be expanded by clicking on the top right-hand side square). Note that due to the large amounts of weather data required the plot results have had to be limited to the previous 4 weeks rather than the previous 6 weeks. If the number of growers expected to subscribe to this service is relatively low, extending the plot data to 6 weeks could be considered.

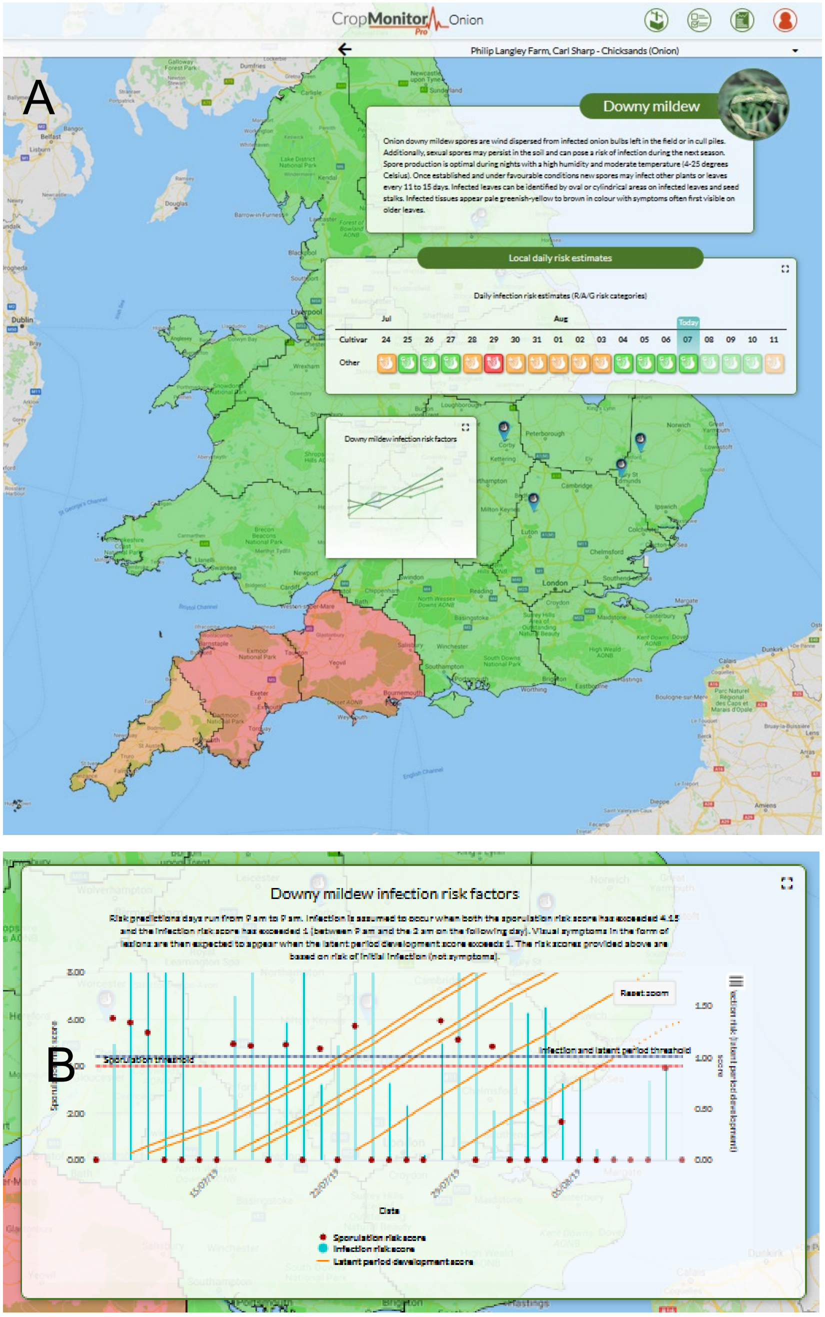

Figure 3. Example of field specific information for Chicksands on 07/08/2019 (A), with a zoomed (and expanded) view of the plot in the right-hand side panel (B).

Access to MILIONCAST

During the current growing season, access to MILIONCAST on CropMonitor Pro can be provided free of charge to the growers that took part in this project. The field for which data were collected for each grower will be registered so that the growers can keep evaluating and using the outputs throughout the rest of the season. This will require the growers to be set up on the system with a secure password. AHDB will also be able to access all 4 of these sites through a separate secure password. In the near future, the onion module will be part of the full CropMonitor Pro subscription service, at which point growers would be able to register single or multiple fields to gain access to local risk predictions for a small subscription fee. Regional risks predictions will remain available free of charge and will not require registration. Note that the subscription charges of CropMonitor Pro will be used for maintenance and expansion of the services available through the platform, making the system more sustainable by achieving continued investment.

Model validation

The predicted sporulation risk scores for each LFD score class are presented in Figure 4. The data suggest that generally the LFD test results marked as high, medium-high and medium for spore presence correlate with higher sporulation risk scores whereas the LFD tests marked as low-medium and low correlate with predictions of low risk. More importantly, with a single exception, all samples with a low or low-medium LFD risk score had a predicted sporulation risk score of 0. This suggests that there is a good correlation between the risk score as predicted by the model and the risk score as assessed by LFD. Further data would be required to quantify the significance of this correlation.

Tables 1 to 4 evaluate the model's ability to predict when visual symptoms will appear within the crop. The tables only contain dates on which either an observation was made in the field and/or when the model predicted lesions of individual infection events would be visible.

At the Thetford site, observations started on the 12th of June, with assessments taking place roughly every other day until the 11th July(Table 1). First symptoms were detected in the field on the 4th of July which almost exactly matches the date of first lesion occurrence as predicted by the model (03/07).

At the Lackford site, assessments started on the 8th of July, with the last assessment being made on the 20th of July (Table 2). During this assessment period no symptoms were detected in the field despite the model predicting visible symptoms on the 9th of July.

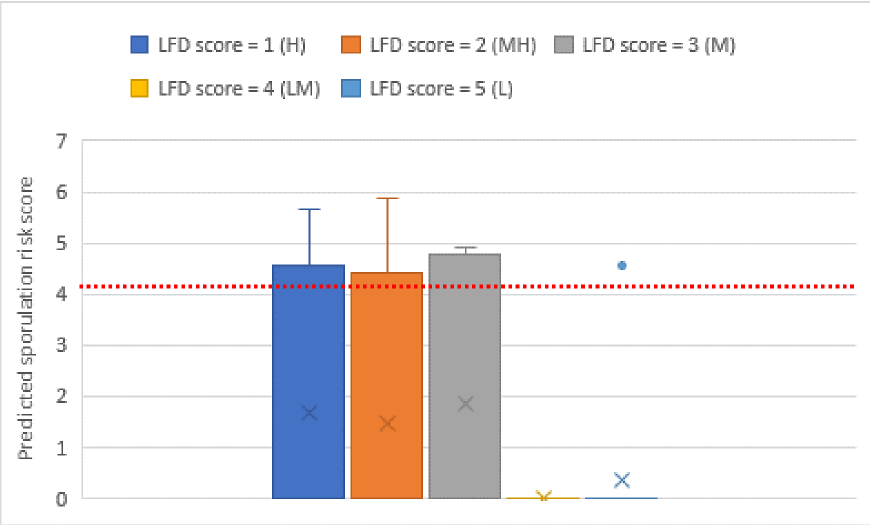

Figure 4. LFD score versus predicted sporulation risk score. In the model sporulation is presumed to occur when the sporulation risk score exceeds 4.15 (red dotted line). Crosses represent means and dots represent outliers.

At the Ripple site, assessments started on the 12th of May, with the last assessment being made on the 20th of July (Table 3; results presented from 23rd May onwards; all observations before this date are negative). First mildew lesions were detected in a nearby crop on the 3rd July, with re-infection reported to be occurring in a nearby crop on the 20th of July (Note that no observations are available between the 9th of July and the 20th of July). The model predicts first symptoms to arise in the field being monitored on the 12th of June, i.e. two weeks earlier than symptoms were reported. Interestingly, sporulating tissues were found in nearby overwintering crops from the 23rd of May onwards. This is not dissimilar to the model prediction of the sporulation threshold first being exceeded on the 17th of May (results not shown). However this first sporulation event is not predicted to lead to symptoms. The model then predicts a further sporulation event of the 18th of May, which is predicted to lead to visible symptoms on the 12th of June. The next 6 sporulation events again are not predicted to lead to symptom expression, after which a further sporulation event on the 5th of June leads to visible symptoms on the 26th of June. In other words, despite the weather conditions frequently being suitable for sporulation to occur, most of these sporulation events do not result in successful infections and therewith symptom expression, which quite closely matches the field data.

At the Chicksands site, assessments started on the 4th of July, with the last assessment being made on the 17th of July (Table 4). During this assessment period no symptoms were detected in the field despite the model predicting a single infection event leading to visible symptoms on the 10th of July.

Shaded lines within the tables signify dates beyond the period of observations for which the model predicted that an infection event would lead to visible symptoms. These data were added because the model suggests that significant epidemics were imminent at all locations with multiple infection events leading to symptom expression within a short time span (1 week).

Table 1. Comparison of dates of predicted symptom expression from the model and dates of observed symptoms in the field - Wretham, Thetford.

Date	Observed symptoms	Predicted symptoms
12/06/2019	no	no
14/06/2019	no	no
17/06/2019	no	no
19/06/2019	no	no
21/06/2019	no	no
24/06/2019	no	no
28/06/2019	no	no
01/07/2019	no	no
03/07/2019	Not assessed	yes
04/07/2019	First symptoms	no
09/07/2019	Not assessed	yes
11/07/2019	Heavily infected	no
22/07/2019	NO DATA AVAILABLE	yes
23/07/2019	NO DATA AVAILABLE	yes
27/07/2019	NO DATA AVAILABLE	yes
29/07/2019	NO DATA AVAILABLE	yes

Table 2. Comparison of predicted symptom expression from the model and observed symptoms in the field - Lackford, Bury Saint Edmunds.

Date	Observed symptoms	Predicted symptoms
08/07/2019	no	no
09/07/2019	Not assessed	yes
14/07/2019	no	no
18/07/2019	no	no
20/07/2019	no	no
22/07/2019	NO DATA AVAILABLE	yes
23/07/2019	NO DATA AVAILABLE	yes
26/07/2019	NO DATA AVAILABLE	yes
27/07/2019	NO DATA AVAILABLE	yes

Table 3. Comparison of dates of predicted symptom expression from the model and dates of observed symptoms in the field - Ripple.

Date	Observed symptoms	Predicted symptoms
23/05/2019	Sporulation in nearby overwintering crop	no
29/05/2019	Sporulation in nearby overwintering crop	no
12/06/2019	Not assessed	yes
26/06/2019	Not assessed	yes
03/07/2019	Mildew lesions appearing in nearby crop	no
09/07/2019	No report	yes
20/07/2019	Re-infection in nearby crop	no
21/07/2019	NO DATA AVAILABLE	yes
22/07/2019	NO DATA AVAILABLE	yes

Table 4. Comparison of dates of predicted symptom expression from the model and dates of observed symptoms in the field - Chicksands.

Date	Observed symptoms	Predicted symptoms
04/07/2019	no	no
08/07/2019	no	no
10/07/2019	no	yes
17/07/2019	no	no
23/07/2019	NO DATA AVAILABLE	yes
26/07/2019	NO DATA AVAILABLE	yes
27/07/2019	NO DATA AVAILABLE	yes

Discussion and conclusions

The MILIONCAST algorithms were successfully connected to the CropMonitor platform. Besides the original graphical outputs (compare Appendix A and Fig. 3B), the CropMonitor platform now also provides daily visualisations for both regional and local risk predictions.

A previous validation performed by Gilles *et al.* (2004) between 1996 and 2001 showed that spore production events were predicted with 81% accuracy and that the error on the latent period model was 1.9 days on average. However, the authors stated that overall model performance in which all model components (sporulation, infection and latent period) were combined was relatively low (61 % of sporulation/ infection events were associated with observed peaks in disease increase). Then again, this is still a significant improvement compared to random predictions (56%; $P < 0.001$). Our validation shows similar trends, although the data available for validation were very limited. In the sporulation validation within this study we found a clear correlation between the score for the LFD used for testing spore presence in air samples and the predicted sporulation risk score. The LFD device is however still under development and needs to be fully calibrated before final conclusions are drawn based on these results and the LFD needs to be tested against a much greater number of samples before it can be concluded whether the observed correlation is significant or not. For the 4 sites tested within the current validation the disease onset was predicted correctly in one of the 4 cases. At the other 3 sites disease alerts were provided before the disease had arisen within the crop. These false positive alerts could lead to unnecessary fungicide applications. There were no sites at which no alert was given despite the disease already having arisen within the crop, which is most important as this could lead to crop losses due to spray applications being applied too late.

Although the overall model performance might not be very high it is promising that the sporulation model is performing well. Disease control is most effective when targeted at the time of first infection rather than when symptoms are clearly visible within the crop. It would therefore be very valuable to do a detailed analysis of the model's capability to predict the first infection event by comparing predicted dates of first infection with the date on which the disease could first be detected in its latent state within the crop (i.e. before symptom expression).

The CropMonitor Pro platform also includes a surveillance platform which allows and encourages subscribers to submit dates of first symptoms observed within the registered fields or on the wider farm. These data could be used for continued further validation of the model's capability to predict first symptoms within a field and to measure potential grower benefits from use of the system.

References

Develash, RK. and Sugha SK. (1997) Incidence of downy mildew and its impact on yield. Indian Phytopathology 50: 127–129.

Gilles, T. and Kennedy, R. (2004). Evaluation of MILIONCAST, a forecaster for onion downy mildew, with historical data. In Advances in Downy Mildew Research 2: 81-89. Kluwer Academic Publishers.

Gilles, T., Phelps, K., Clarkson, JP. and Kennedy, R. (2004). Development of MILIONCAST, an improved model for predicting downy mildew sporulation on onions. Plant Disease 88: 695-702.

Kennedy, R. (2019). Delivery of a Diagnostic test pilot scheme for Brassicas and Onions. AHDB project FV 456.

Wakeham, A. (2008). Evaluation of an integrated disease management system to ascribe risk of downy mildew disease on commercial salad and bulb onion crops in the UK. AHDB project CP 099c p. 1-43.

Appendix A: MILIONCAST model descriptions provided by AHDB

The text below is a verbatim report provided by AHDB regarding the functionality of the current MILIONCAST (Downy Mildew – *Peronospora destructor*) algorithms.

Introduction

The MILIONCAST model consists of three models, one each for prediction of sporulation events, conducive conditions for infection and duration of latent period prior to symptom development. The model uses weather data for the previous six weeks. For the sporulation and infection models it produces a score that indicates how likely it is that sporulation or infection could have occurred. For each day on which it is predicted that both sporulation and infection would have occurred, it runs the latent period model to predict when lesions will appear.

Weather Inputs

1. Air Temperature ℃
2. Humidity %
3. Leaf Wetness mV
4. Rainfall mm

User Inputs

1. Latitude ° (used to calculate sunset time)

Outputs

The MILIONCAST output consists of a set of 3 graphs. The first is a graph indicating sporulation events. The height of the bars indicates the chance of sporulation having occurred in the previous 24 hours. Conditions have been conducive for sporulation if the bar exceeds the threshold of 4.15. A bar is coloured red if infection has also been predicted to have occurred. The infection graph shows progress towards an infection event. Conditions have been conducive for infection if the threshold of 1.0 is crossed. The latent period graph shows

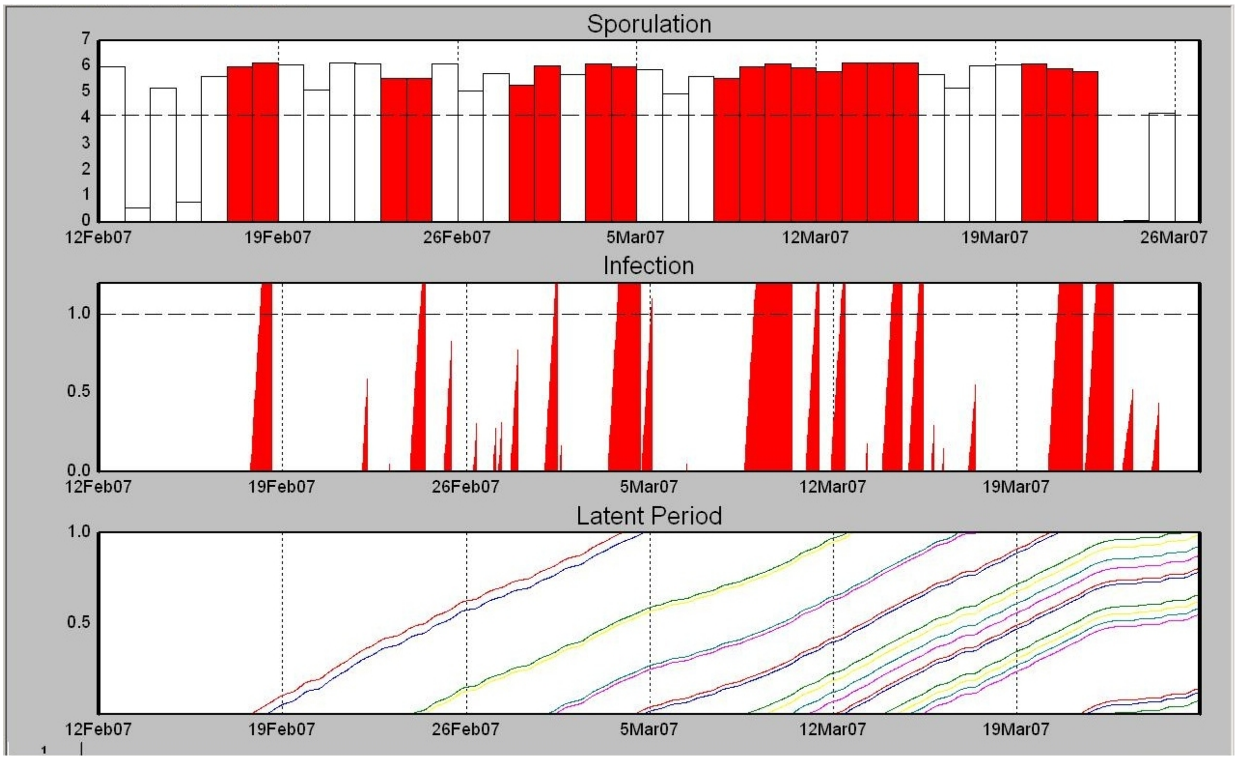

Figure 1. Graphs of Sporulation, Infection and Latent Period

progress towards lesion appearance from potential infection events on the days when both sporulation and infection were predicted. Lesions appear when the threshold of 1.0 is crossed.

Model Description

<u>Sporulation</u>

The sporulation model treats a day as running from 9:00am – 9:00am. It uses half hourly readings. Progress towards sporulation only occurs between sunset and 9:00am the next morning and is inhibited if it has been too warm during the afternoon, from noon to 17:30.

The sporulation score, SC, is calculated each day as follows:

foreach reading from noon to 17:30


```
        inhib += airTemp
mcon01 = 0.0
cumSpor = 0.0
foreach reading
        if (between sunset and 9:00am) && humidity > 92
                mcon01 += 0.5
                conC = gammaDist(alphaC, betaC, gammaC, airTemp)
                conCPrime = conC / log10(exp(1.0))
                conM = 1.0 / gammaDist(alphaM, betaM, gammaM, airTemp)
                conRHDeter = pow((1.0 - r), (100.0 - humidity))
                conRate = (b * conCPrime * exp(exp(-exp(-b * (mcon01 -conM))) * conCPrime - exp(-b *
                  (mcon01 - conM)) - b * (mcon01 - conM))) / 2.0
                cumSpor += (conRate * conRHDeter)
if inhib >= 386.7
        cumSpor = 0.0
SC = log10(cumSpor + 1.0)
```

Where gammaDist(alpha, beta, gamma, airTemp) is given by

$$gammaDist(\alpha, \beta, \gamma, T) = \frac{\gamma T^{\alpha-1} e^{\frac{-T}{\beta}}}{\beta^{\alpha}} \Gamma(\alpha)$$

With parameters

- alphaC = 2.15
- betaC = 11.95
- betaC = 212.92
- alphaM = 2.614
- betaM = 6.926
- gammaM = 4.0138

- b = 0.903
- r = 0.3968

Infection

The infection model produces an indication of whether infection could have occurred. The Infection Prediction, IP, is calculated as follows:

```
if leaf wetness > 400

mcon04 = 1.0 / (2.0 * (20.26 – 1.801 * airTemp + 0.0682 * airTemp * airTemp)

else

    mcon04 = 0.0

mcon05[0] = mcon04

mcon06[0]= mcon05[0]

foreach record starting at the second

    if leaf wetness > 400

        mcon04 = 1.0 / (2.0 * (20.26 – 1.801 * airTemp + 0.0682 * airTemp * airTemp)

    else

        mcon04 = 0.0

    mcon05[i] = mcon05[i-1] + mcon04

    if mcon05[i] == mcon05[i – 1]

        mcon06[i] = mcon05[i]

    else

        mcon06[i] = mcon06[i -1]

    IP[i] = mcon05[i] – mcon06[i]
```

Latent period

The latent period model predicts progress towards lesion appearance from a predicted infection event. An infection event happens when the sporulation score for a day exceeds the sporulation threshold during an infection period. An infection period is defined by the Infection Prediction being greater than zero.

The model first finds the beginning and end of each infection period using the Infection Period score from the infection model.

For each day that the Sporulation Score has exceeded the sporulation threshold of 4.15 it checks to see if infection could have happened. Infection has happened if one of conditions is true.

1. An infection period has started before 09:00 on the sporulation day and the infection prediction score has crossed the threshold of 1.0 by the earlier of 02:00 the next day or the end of the infection period. The latent period starts at 09:00 on the sporulation day.
2. An infection period starts after 09:00 on the sporulation day and before 02:00 the next day. The latent period starts when the infection period starts.

For each latent period that has been discovered, progress toward lesion appearance is calculated by accumulating the following function from the start of the latent period until the current time.

latent = 0

foreach record from latent period start to now

*latent = latent + gammaDist(alphaL, betaL, gammaL, T) * timestep*

where

- *alphaL = 4.92*
- *betaL = 5.69*
- *gammaL = 3.479*

Lesion appearances occurs when the latent period progress reached.

