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QUATERNARY CONCEPT OF INTEGRATED PEST MANAGEMENT (IPM), DEVELOPED FOR THE CONTROL OF CERCOSPORA LEAF SPOT IN SUGAR BEETS

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ABSTRACT

A holistic concept, involving four elements of IPM, has been developed for the control of Cercospora leaf spots (CLS) in sugar beets. The system may be characterized as quaternary where the single elements are linked with each other and the combination provides a complete system. The concept should contribute to the sustainability of sugar beet cropping as it helps to reduce the chemical load on the environment.

The quaternary concept of IPM enables yield optimization along with the reduction of the fungicide use to an essential minimum. The calculation of daily infection values (DIV) and cumulative addition (c-DIV) is used for a (i) negative-prognosis, which determines the disease free period. After c-DIV has exceeded thresholds, risk of first symptom appearance is increasing and, because negative-prognosis is not able to predict the exact time of the epidemic onset, a field monitoring is necessary to check the actual incidence in the field. C-DIV thresholds are variable and determined as 6, 9 and 12, valid for highly, moderate and low susceptible cultivars respectively. Subsequently, diagnosis and disease scoring proofs the exceeding of (ii) spraying thresholds. Spraying thresholds are the tool to pinpoint the exact timing of fungicide sprays to optimize the efficiency and to get the most possible benefit. The threshold for an initial treatment is defined as a leaf infection frequency of 5 %, respectively 40-50% for a following treatment based on a sample of 100 leaves. Nevertheless, spraying thresholds are corresponding with very early stages of the epidemic. Yield and quality of sugar beets is not affected through leaf incidence as defined by spraying thresholds. Therefore, the tolerable disease level at harvest is determined by the (iii) economic damage threshold of 3-5% of infected leaf area. Based on the economic damage threshold, (iv) loss prediction gives insight, whether the future progress of an epidemic will lead to threshold exceeding at scheduled harvest time and therefore, whether a fungicide treatment is necessary or not.

Additional keywords: Beta vulgaris, *Cercospora beticola*, epidemiology, disease control, sustainability.

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INTRODUCTION

In many parts of the world, *Cercospora beticola* is the most important leaf spot disease of sugar beets. Among the diverse range of measures aimed to protect sugar beets from fungal leaf pathogens, only fungicides enable an efficient interruption of an actual epidemic and thus secure crop yield and quality. The integrated crop protection approach thus explicitly includes fungicide applications, taking into account that even by applying all available preventive procedures (crop rotation, soil cultivation, resistant cultivars, etc.), fungicide applications can generally not be replaced by other measures when crop yield and quality is threatened by an actual epidemic (3). In view of promotion sustainable land use, IPM programs are directed to reduce the chemical load on the environment (1). Following these principles, fungicide applications are only then justified, when yield losses are to be expected with a high probability.

Routine measures based on scheduled spray regimes are oriented to an average risk; however, the damage potential is variable to a big extent, dependent on year, site and cropping measures. Therefore, we developed an IPM-System, which is reacting flexible, according to the present epidemic development (16,20,25). On the primary, the innovation of our model lies on the effective combination of IPM tools, because, every single tool is affected with some constraints to fulfil the demands of Integrated Pest Management as mentioned above. Hence, the model involves the prediction of incidence (16,18,23,24), spraying thresholds (13,18,25-27), the determination of the economic damage threshold (16,18-20), where the prediction of yield losses is based on (18,19,21,22). The diagnosis is outstanding due to its key-function, because definitely, there is no IPM to be conducted without exact identification of disease symptoms. Or in simple words, the tools are not working, if the symptoms are ignored or confused. In general, these principles of combining IPM-tools may be applied for many other host-parasite systems as well, in particular, where an initial infection is tolerable. This is the case, if quality and yield of the crop is not affected at the disease level of a spraying threshold, and, on the other hand, if fungicides are available, high effective in controlling disease at initial epidemic stages.

The presentation, following now, is mainly focused to the reasons why IPM-tools have to be linked with each other. Therefore, detailed insights in modelling of the different parts may be allowed to be neglected and substituted through reference of citations, where more detailed information is provided.

MATERIALS AND METHODS

Field experiments. The program involved trials in a randomised block design with multiple factors (block n=4 replications, cultivar n=1-5, fungicide treatment resp. thresholds n=4-12). The data set (n=109 field experiments) consists of a eleven years study (1993-2003, 11 sites) in Southern Germany.

Disease severity was recorded from the beginning of June until October. On first recording date, forty beet plants (10 per plot) were randomly selected. At weekly intervals, the number of green and dead leaves as well as the percentage of necrotic leaf area was established on selected plants. Necrosis estimation of single leaves was performed by using a rating scheme (2). Based on single leaf records, mean calculation of plant and/or leaf infection frequency as well as disease severity was performed. If diagnosis was not sure, the causal agent of leaf spots was fixed through the occurrence of hyphal structures.

Efficiency of epidemic oriented spraying thresholds was compared to relatively disease free plots (3 fungicide sprays fixed by calendar schedule). Yield was measured after a machine harvest of three rows in the centre of a plot (11 rows, 7 m). Yield analysis was supported by sugar industry and involved measurements of yield mass, sugar content as well as contents of impurities (αAmino-Nitrogen, Sodium, Potassium).

Collection of weather data was provided by electronic stations (temperature, precipitation, air relative humidity), either after "Weihofen" (Thies, Göttingen) or "Lambrecht".

Model description

Negative-Prognosis. Epidemic onset (target variable of negative-prognosis) was defined as the time when ≥50% of beet plants were infected, resp. showed at least one lesion on one leaf. The influence of weather on the epidemic onset was assessed through the calculation of daily infection values (DIV) (23). The influence of temperature was expressed by proportions relative to the optimum of the latent period, found under greenhouse conditions. Leaf wetness is obligate for infection and existed with 75 % probability, if air relative humidity was higher than 90%. Therefore, the calculated values were set to 0 in cases of air relative humidity ≤90%. Each epidemic onset of field studies (n=69) was set in relation to the cumulative DIV (c-DIV). Start of DIV-addition was the variable time of canopy closure and therefore flexible, in order to match the differing canopy development. Time of canopy closure has a distinct impact on epidemic onset due to the changes of microclimate, resulting in longer leaf wetness periods and higher air relative humidity (16,17). A "Negative-Prognosis" was defined by using the minimum sum of c-DIV as a threshold, where, when exceeded, the occurrence of incidence cannot be excluded anymore.

Loss prediction is based on real case studies of disease progression in the field. The model is therefore empirical on one hand and deterministic on the other hand. Deterministic, because prediction depends on data input of actual date, actual disease incidence (% infected leaves in the range of 3-50%, sample n=100 leaves) and cultivar susceptibility, which determine the forecast of future disease progression. First step of development was selection of case studies depending on the date (calendar week) of epidemic onset and resistance of cultivar (highly and low susceptible). The mean, minimum and maximum of disease progression was calculated and forecast of disease progression was performed by the mathematical model:

$DS = DSmin + DSmax / (1 + \exp(-(CW-a)/b))$,

where DS = disease severity, DSmin = minimum of disease severity, DSmax = maximum of disease severity, CW = week of calendar, a and b = variable depending on actual DS and cultivar resistance.

In addition, loss prediction (yield mass, sugar content, recoverable sugar yield) is calculated, depending on scheduled harvest time and expected yield. This prediction is based on the relationship of AUDPC (Area Under Disease Progress Curve) (4) and loss, which is expressed through the relative yield difference of untreated and healthy (18-20).

RESULTS

Variation of disease onset time. First step in developing a disease prediction model was an empirical analysis of disease onset variation. Fig. 1 reveals the total extent of the period, where a disease onset is to be expected. The frequency of epidemic onset is related to the canopy closure. Canopy closure is an important event in the growing season, because during the subsequent period the microclimate is changing, in particular leaf wetness periods and relative air humidity (rH) are extended when the density of leaf mass is increasing.

Youth development of sugar beet until the emergence of leaf number 14-16 is completely free of CLS infections. In relation to the canopy closure, first symptoms appeared after 3 weeks at the earliest and 12 weeks at the latest (Fig. 1). The peak appeared 6-8 weeks after canopy closure in high susceptible cultivars, respectively 7-9 weeks when cultivar reaction was low susceptible. Overall, a wide variability of epidemic onset was evident and the question is how to explain this variability by differing weather as a causative factor. Only if a proper explanation is possible for past events it’s opportune to perform valid predictions during a current season.

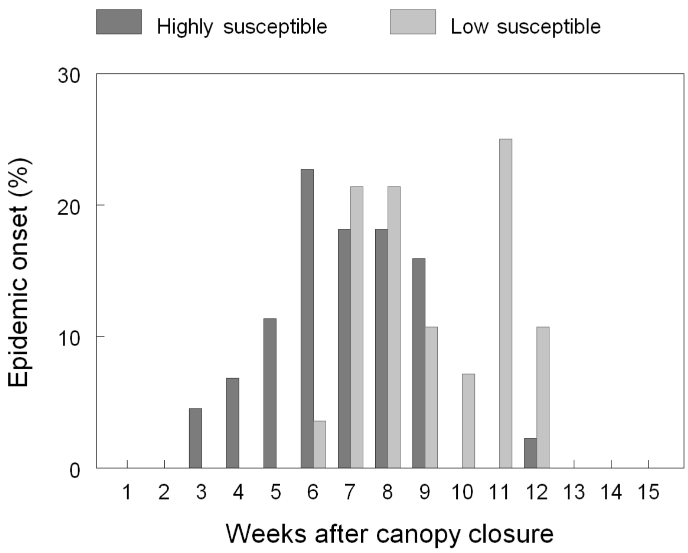

Fig. 1. Variation in epidemic onset times[a], depending on the time of canopy closure (After Wolf, P.F.J. and Verreet, J.A., 2002).

[a]Epidemic onset is defined as a plant infection frequency of 50%, in other words, when every second beet plant is showing symptoms.

Prediction of disease onset. First step in explanation of epidemic onset variation was to create a value which can describe the relationship between weather and epidemic onset. The IPM sugar beet model calculates the probability of infection through daily infection values (DIV). The latter are calculated through specific mathematical algorithm which incorporate the effect of moisture and temperature. In order to describe the relationship between disease onset and weather conditions, the cumulative DIV (c-DIV) was introduced by addition of the daily values (16). The procedure is displayed in figure 2. In the period from row closure till epidemic onset, DIV ranged from 0.06 to 0.61 (Fig. 2-A). Higher DIV values concur with higher humidity and precipitation (Fig. 2-B). In this field study, a c-DIV of 9.8 was determined. The period of c-DIV is held flexible from canopy closure to disease onset. The flexible start of c-DIV considers the effect of crop development on microclimate due to longer leaf wetness duration and relative humidity within the crop after canopy closure (5,17).

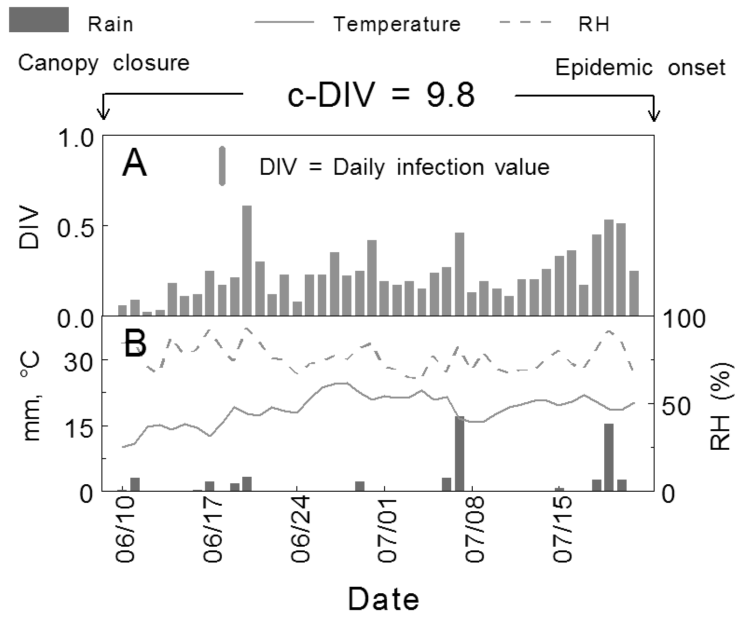

Fig. 2. Example, showing the calculation of daily infection values (DIV)[a] based on weather data (After Wolf, P.F.J., 2002).

[a]The procedure in detail and formula for calculation are published by Wolf et al. (2001, 2005).

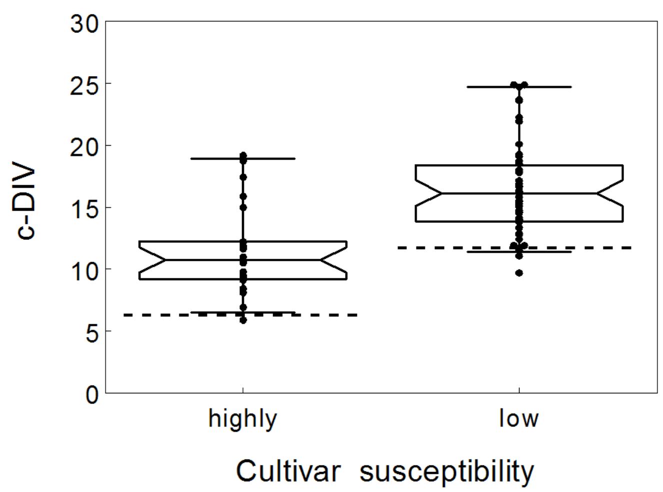

Fig. 3. Variation of the cumulative daily infection value (c-DIV) of *Cercospora beticola* calculated with weather data from canopy closure to epidemic onset based on 22 and 47 field trials with sugar beet cultivars of high (degree of susceptibility = 5-6) and low susceptibility[a] (degree of susceptibility = 4); epidemic onset was defined as the time when a disease incidence of 50% was reached (After Wolf, P.F.J. and Verreet, J.A., 2005). Dotted lines are indicating minimum values of c-DIV when a disease onset occurred.

[a]Cultivar susceptibility is classified by degrees from 1-9, 1 = lowest and 9 = highest susceptibility according to the scale of Deutsches Bundessortenamt.

The target is now to explain the different disease onset times which appeared in the field studies over different years, cultivars and sites. This is done by comparisons of c-DIV and the expectation that the extent of variation will be small respectively will be reduced when the effect of weather is considered by the aid of c-DIVs. As a first result, cultivar resistance has a big impact on c-DIV and therefore has to be considered as an important determinant (Fig. 3). The most crucial conclusion is, however, that the differences between minimum and maximum values of c-DIV range from 7 to 19 for highly susceptible cultivars respectively from 12 to 25 for cultivars with a lower susceptibility. These values indicate a relatively high variation and, therefore, don't explain the epidemic variances of past field experiments satisfactorily. As a consequence, this approach has to be assessed as not suitable to predict the precise time of epidemic onset in future growing seasons.

The Quaternary IPM-concept

Due to insufficient efficiency of the disease prediction as described above we introduced complementary tools. The model may be characterized as quaternary by involving four elements (Fig. 4), which are i) negative-prognosis of disease incidence (16), ii) spraying thresholds (13,14,20,26), iii) the determination of the economic damage threshold (16,19,20), where iv) the prediction of yield losses is based on (20,21). The diagnosis is outstanding due to its key-function, because definitely, no IPM can be conducted without an exact identification of disease symptoms.

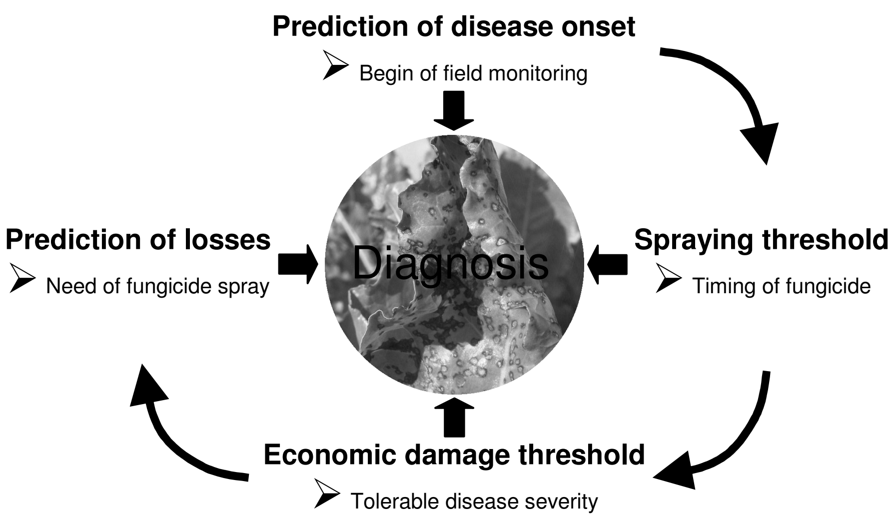

Fig. 4. The Quaternary IPM-concept, it's elements and the order to use them during a growing season (After Wolf, P.F.J. and Verreet, J.A., 2003).

(i) Negative-prognosis of disease onset. Negative-prognosis is valuable to save efforts in disease observation and it provides information, when to begin the field monitoring**.** During a growing season, it's the first tool to be applied. Because the attempt of predicting the exact time of the epidemic onset has failed, the only option is the converse one of predicting periods with a high probability that no infection will occur. The disease-free period can be determined by a negative-prognosis in setting minimum values of c-DIV when a disease onset occurred (Fig. 3). The threshold value to be established here is 6-7 for highly susceptible varieties whereas in varieties of lower susceptibility disease onset was absent until a total of c-DIV = 12. When these thresholds are exceeded, disease onset cannot be excluded anymore and has to be expected with increasing probability. For these definitions the best approach in starting addition of DIV, the flexible origin of c-DIV by canopy closure, is applied (16).

The system and the use of the negative-prognosis are demonstrated in Fig. 5. Based on the weather conditions (Fig. 5-A), the daily infection values from canopy closure on are calculated (Fig. 5-B). The date when disease onset of *C. beticola* cannot be ignored any longer is deduced from the c-DIV. (Fig. 5-C). This is revealed at the crossing point of c-DIV and minimum criteria, i.e., in this case July 15 for highly susceptible varieties and August 4 for low susceptible varieties. The monitoring of the crop has to start then in order to determine the actual disease onset.

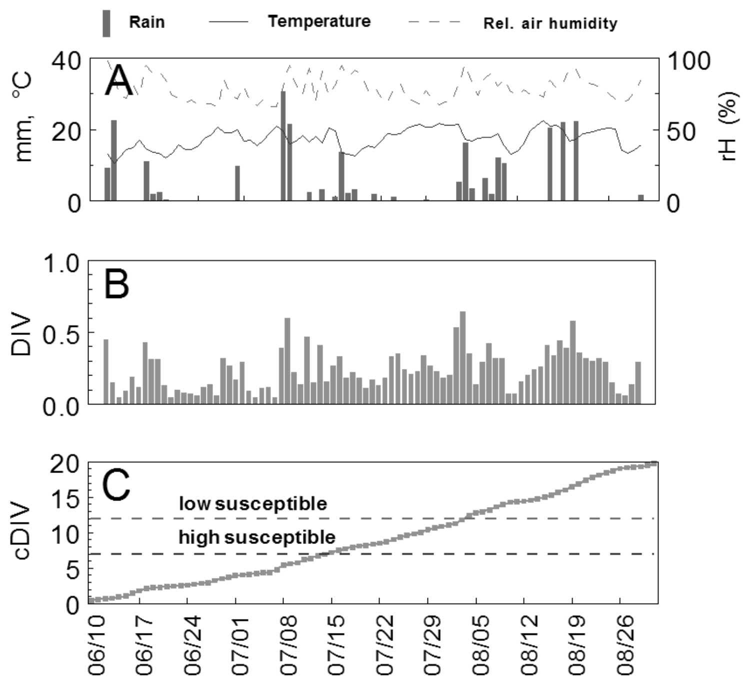

Fig. 5. Example of the practical use of negative-prognosis for Cercospora leaf spot based on a field trial in southern Germany (site Moosham 2001): A, daily values of mean air temperature, mean relative humidity (rH), and rainfall; B, weather-based calculation of daily infection

values (DIV)[a]; C, negative-prognosis based on cumulative DIV (c-DIV), where summation commences with canopy closure. Dotted lines indicate the thresholds when epidemic onset cannot be excluded any longer for highly and low susceptible cultivars.

[a]Formula for calculation of DIV is described by Wolf, P.F.J. and Verreet, J.A. (2005).

(ii) Spraying thresholds. Spraying thresholds determine the optimum date of fungicide applications. During the monitoring, the crucial point is the diagnosis and quantification of diseases as well as to proof the exceeding of spraying thresholds. In order to match the target of optimizing the efficiency of fungicide sprays, successive stages of the epidemic were assessed for thresholds, pinpointing the exact time of application. The results show that only sprays during the epidemic onset of disease are effective and suitable for a practical use (13,14,20,25,26). Applications should be carried out at a disease severity between 0.01 and 0.2 % (Fig. 6). These thresholds are corresponding with a leaf infection frequency of 5% respectively 40-50% based on a sample of 100 leaves picked up from the middle of the leaf mass. Later timed applications are decreasing the efficacy to less than 80 %. Nevertheless, epidemic thresholds as a single tool are not sufficient to keep in the above mentioned targets of IPM. The reason is, because a spraying threshold is indicating the time for a highly effective spray but not the significance of an economic damage.

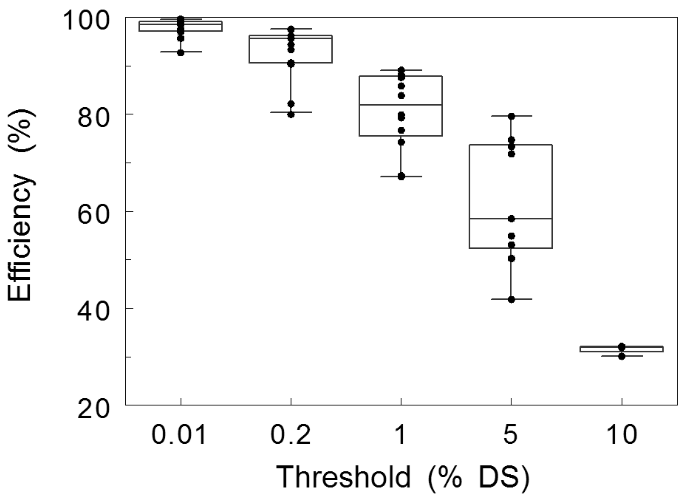

Fig. 6. Efficiency of successive stages of the epidemic used as thresholds for the timing of fungicide sprays. Each single point (mean of 4 replications = plots) is representing the result of one field experiment, for instance of one year, site and cultivar (After Wolf, P.F.J. and Verreet, J.A., 2001).

Legend for Box-Whisker graph: The box shows the range between the 25th and 75th percentiles, the horizontal line indicates the median value, the whiskers extend from the edge of the box to the 5th and 95th percentiles.

(iii) Economic damage threshold. Unlike the spraying threshold, the economic damage threshold defines the tolerable disease level at the end of the season (19,20). The definition of the economic damage threshold is based on the relationship of disease severity and sugar loss (Fig. 7). The disease-loss relationship shows a linear character. Sugar losses ranged from 0-35%, but 3-5 % of infected leaf area (DS) may be accepted at the end of the season. At this disease level, losses of recoverable sugar are 2-3 % where application costs would equalize the benefits of disease control.

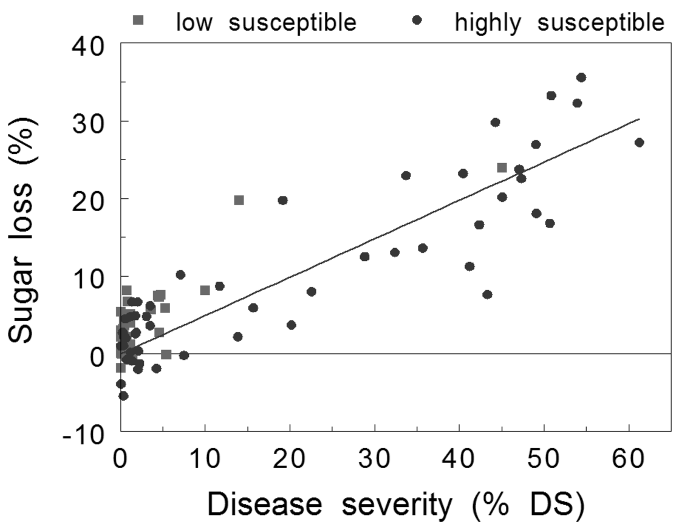

Fig. 7. Disease loss relationship for *Cercospora beticola* in sugar beets; definition of the economic damage threshold = 5 % DS, corresponding sugar loss = 2-3% (recoverable sugar yield).

Regression (p=0.05): Sugar loss (%) = 0.45 * DS $r^2 = 0.80$

(iv) Prediction of losses. When the spraying threshold is exceeded, loss prediction has to be conducted because the disease level of a spraying threshold does not cause an actual damage. Depending on site-specific conditions, the epidemic needs a period of at least five to ten weeks to proceed from the disease level of the spraying threshold (0.01 DS) towards the economic damage threshold (3-5% DS) (19,20). Hence, the importance of threshold exceeding time, cultivar resistance and scheduled harvest time for the prediction of yield losses is evident. The necessity of a fungicide application is indicated, when the predicted disease severity exceeds the damage threshold before the scheduled harvest time. The weather is not referred to, because predictions are to be done for more than four weeks and weather forecasts are not reliable for such a long period.

Figure 8 displays three examples of different threshold exceeding times. For instance, if the spraying resp. acting threshold is reached on July 23, a high progressive epidemic is predicted to develop. There is an absolute need of fungicide application, because harvest time normally begins later, at least under conditions in Central Europe. Fungicide application is only conditional, if the spraying threshold is exceeded on August 6. Disease progression is rather moderate and it depends on harvest time, whether there is a yield risk. In this example, fungicide applications can be avoided, if harvest takes place before October. The dotted line marks the progression after exceeding the spraying threshold on August 20. In this case, definitely no fungicide application is necessary. The progression remains below the damage threshold up to the end of the season.

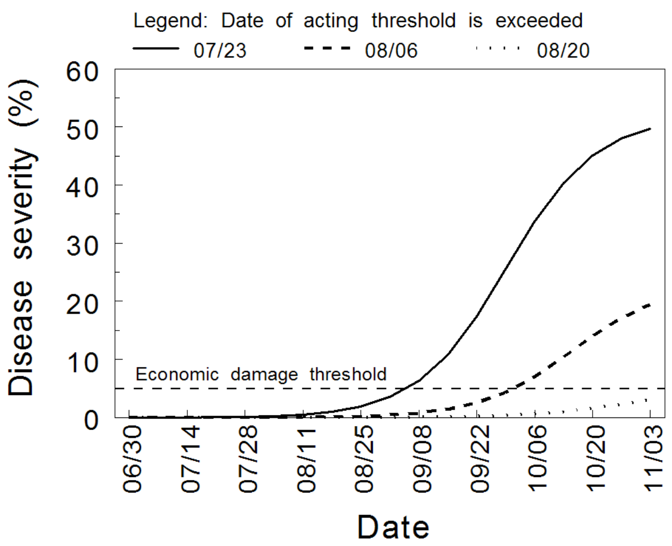

Fig. 8. Prediction of disease progression dependent on the time of threshold exceeding (threshold = 0,01 % DS, cultivar low susceptible); a fungicide spray is necessary, if the economic damage threshold is exceeded before the scheduled harvest time (Modified after Wolf, P.F.J., Klinck, H., Verreet, J.-A., 2004).

DISCUSSION

IPM concepts include precautionary cropping measures as crop rotation, soil preparation, cultivar resistance, etc. in order to interrupt the infection chain. Despite putting respect on these principles, occurrence of epidemic diseases may not be excluded entirely. In many cases, diseases are present every season, where severity of disease varies to a more or less big extent, depending on environmental factors (3). Fungicides remain the only mean of interference with an actual epidemic and thus to safe yield and quality of the crop. On the other hand, concerns with synthetic chemicals in the environment encouraged scientists to develop IPM-concepts to reduce the chemical load on the environment on one hand but to optimize the economic benefit on the other hand.

Diagnosis is surely to be seen as a key factor of any IPM-system. Among the basic factors of IPM model design, pathogen progression studies in the field are essential which also include assessment of the economic losses. The resulting data enable the determination of control and damage thresholds as well as the development and validation of disease prediction models. In this context, the different IPM elements require a reliable identification of the disease causing pathogens to guarantee the validity of the data. Without a correct diagnosis, an IPM model can neither be developed nor successfully applied (10-12,16,20).

The goodness of disease prediction models may be assessed by the ability to explain the variation in disease onset times. The relationship between the influence factors and the epidemic onset is crucial here. Hence we have to realize, that our comprehension of disease influencing factors is still poor since the epidemic behavior of pathogens isn't only dependent on weather but much more complex embedded in the ecosystem. Indeed, till today there is no prediction model existing for foliar sugar beet diseases, which is able to pinpoint the exact time of disease onset in order to match the target of deciding on plant protection measures directly (6-9,15). Overall, disease prediction models have just to be assessed as approximations of reality. In addition, they are only valid under certain frame conditions concerning the regional cropping situation (climate, growing density, cropping measures and techniques).

In many cases, the prediction of disease is assumed of main importance for the development of guidelines concerning the optimization of pest management methods. Nevertheless, how to integrate them in IPM-concepts is depending on the specific implications of a given host-parasite system. In particular, to what extent early infections may be tolerated has to be assessed from a practical view. For several pathogens, tolerance exists not at all, either deduced from food quality criteria or from an insufficient efficiency of fungicides which, in many cases, do not control even the early stages of an epidemic. This is in particular valid for apple scab (*Venturia inaequalis*) derived from quality demands or for potato late blight (*Phytophthora infestans*) due to the minor curative efficiency of available fungicides. Therefore, when fungicides have to be applied protective, a weather data-supported disease prediction remains as the only method to handle the time of application flexible according to the current risk of infection. Other crops tolerate at least initial infections without any yield or quality loss and, in addition, early stages of an epidemic can efficiently be controlled with fungicides. This in particular is valid for cereal and beet leaf diseases where decisions concerning fungicide applications are therefore primarily based on threshold values and disease prediction provide only additional information about the risk of epidemic onset, especially when to begin with the field observations. During the field monitoring, the exceeding of pathogen specific thresholds is the crucial point, because they pinpoint the exact time of a fungicide spray. Decision periods indicate if the time of threshold exceeding is including a yield risk. Loss prediction, based on calculation of disease progression in relationship with the economic damage threshold may precise the yield risk. Only when disease progression is predicted to exceed the economic damage threshold before scheduled harvest time, a fungicide treatment is necessary. Our quaternary IPM-system considers the above mentioned constraints of single IPM-tools and, therefore, combines them to an effective concept.

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