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SIMONTO-Lupin: an ontogenetic simulation model for lupin species (*Lupinus angustifolius*, *L. luteus* and *L. albus*)

SIMONTO-Lupine: Ein Ontogenesemodell für Lupine-Arten (*Lupinus angustifolius*, *L. luteus* und *L. albus*)

Abstract

The development of the infection of *Colletotrichum lupini* is in addition to temperature and leaf wetness duration strongly dependent on the plant development stage (BBCH). For this reason a simple ontogenetic model (SIMONTO-Lupin) for the three lupin species *Lupinus angustifolius*, *L. luteus* and *L. albus* was developed and integrated into the decision support system SIMCOL which deals with the disease management of the pathosystem *C. lupini* – *L. angustifolius*. For the simulation of the crop stages a temperature development rate was modelled. Besides literature data about 180 data series from national variety and fungicide trials of blue, yellow and white lupin were used as data base for modelling SIMONTO-Lupin.

For the model validation 240 data sets of blue lupin of national variety and fungicide trials for the years 2006–2009 were available. These data sets were independent of the data sets used for model development.

The model SIMONTO-Lupin represents particularly the important period of flowering. The validation of the model (difference between observed and simulated growth stage max. 7 days) for the BBCH stage 61 (beginning flowering) showed 85% and for the stage 69 (full bloom) about 75% correct forecasts. Other validation criteria like the subjective validation showed about 88% correct forecasts. The validation by means of linear regression achieved, on average, a coefficient of determination of 0.984.

Key words: Lupin, temperature development rate, growth stages, ontogenetic model

Zusammenfassung

Die Befallsentwicklung von *Colletotrichum lupini* ist neben der Temperatur und der Blattnässedauer stark abhängig vom aktuellen BBCH-Stadium des Lupinenbestands. Aus diesem Grund wurde für das Entscheidungshilfesystem SIMCOL, das sich mit dem Pathosystem *C. lupini* – *Lupinus angustifolius* beschäftigt, ein einfaches Ontogenesemodell (SIMONTO-Lupine) für die drei Lupinenarten *L. angustifolius*, *L. luteus* und *L. albus* entwickelt und integriert. Zur Berechnung der Bestandesentwicklung wurde eine temperaturabhängige Entwicklungsrate modelliert. Datengrundlage für die Modellierung von SIMONTO-Lupine waren neben Literaturdaten ca. 180 Datenreihen aus Landessortenversuchen, Beiz- und Fungizidversuchen von blauer, gelber und weißer Lupine. Für die Überprüfung des Ontogenesemodells SIMONTO-Lupine standen 240 Datenreihen der blauen Lupine von Landessortenversuchen, sowie Fungizid- und Beizversuchen aus den Jahren 2006 bis 2009 zur Verfügung. Diese Daten sind unabhängig von den zur Modellerstellung verwendeten Daten.

Das Modell SIMONTO-Lupine bildet insbesondere den wichtigen Zeitraum der Blüte optimal ab. Die Trefferquote (Differenz zwischen Bonitur und Simulation max. 7 Tage) des BBCH-Stadiums 61 lag bei 85% korrekten

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Prognosen und des Stadiums 69 bei 75% korrekten Prognosen. Bei der subjektiven Validierung wurde eine Trefferquote von 89% erzielt. Die Validierung mittels Linearer Regression erzielte im Mittel ein Bestimmtheitsmaß von 0,984.

Stichwörter: Lupine, Temperaturabhängige Entwicklungsrate, BBCH-Stadien, Ontogenesemodell

Introduction

The simulation of the development stages of cultivated plants has different purposes. The prediction of the different stages of development of one culture can be used to verify the growing performance of the plants during the season or to identify periods for the correct application of pesticides. Certainly one of the most interesting aims is the integration of an ontogenetic model in a decision support system (DSS) for crop protection. An integrated ontogenetic model can for example be used to indicate periods of major plant susceptibility, to make plans for monitoring and survey activities or for the scheduling of treatments. The Central Institution for DSS in Crop Protection (ZEPP) has increased its experience in developing ontogenesis models with the creation of the SIMONTO (**SIM**ulation **ONTO**genesis) models for cereals and oilseed rape in the last years (FALKE et al., 2006, 2008; ROSSBERG et al., 2005).

During the realisation of the DSS for the pathosystem *C. lupini* – narrow leaf (blue) lupin (*L. angustifolius*) – a simple ontogenetic model (SIMONTO-Lupin) was developed to indicate growth stages with high susceptibility.

Plant growth stages are usually described in agriculture numerical (LARGE, 1954; HAUN, 1973; ZADOKS et al., 1974). One of the most common scales used for both mono- and dicotyledonous plants is the BBCH decimal code growth scale developed in 1992 in Germany (HACK et al., 1992). The scale describes the plant growing from sowing (decimal code 0) to the natural death of the plant (decimal code 99).

From the studies by DRACUP and KIRBY (1996a) a BBCH growth scale for lupin was developed and described (RÖMER, 2007) and it is commonly used for all purposes regarding this culture. Aim of this work was to build a model able to simulate this growth scale depending on the seasonal time for the three main lupin species (*L. angustifolius*, *L. luteus* and *L. albus*).

Model development

Plant growing is strongly correlated with a complex of environmental factors. Some of them like the nitrogen and water availability are correlated with the soil characteristics. Other factors like temperature, rainfall and photoperiod are directly involved in the photosynthesis activity.

Since the aim of this model is to predict the occurrence of phenological stages, a simple approach using only the temperature as a limiting factor for the plant development was used for the modelling of SIMONTO-Lupin.

The simple model basis can be written as follow:

[1] $$\text{BBCH } x = (f)\ \Sigma\ \text{LDR}$$

Where:
BBCH x = Plant growth stage
Σ LDR = Sum of the lupin development rate from sowing to BBCH x

Lupin development rate (LDR)

Data of lupin plant development depending on temperature were derived from literature (DRACUP and KIRBY, 1993; FARRÉ et al., 2004) and transformed to obtain a development rate with minimum, optimum and maximum temperature at 0, 20 and 30°C respectively. LDR was obtained by interpolating this data using the Beta-Hau function (HAU, 1988):

[2] $$LDR(T) = LDR_{opt}\,[(T-T_{min})/(T_{opt}-T_{min})]^{n(Topt-Tmin)/(Tmax-Topt)}\,[(T_{max}-T)/(T_{max}-T_{opt})]^{n}$$

Where:
LDR (T) = Lupin development rate depending on the temperature
LDR_{opt} = Optimal lupin development rate
T = Temperature
T_{min} = Minimum temperature for plant development
T_{opt} = Optimum temperature for plant development
T_{max} = Maximum temperature for plant development
n = Equation parameter

The estimated parameters of the equation are given in Tab. 1, the interpolated function in Fig. 1.

Compared to literature data (DRACUP and KIRBY, 1993; DRACUP and KIRBY, 1996b; FARRÉ et al., 2004) the result of the interpolation does not modify the minimum and maximum temperature for the plant growing and estimates an optimum temperature at about 19°C.

Tab. 1. Estimated parameters for the lupin development rate (LDR)

Parameter	Value	S.E.	p	r^2
LDR_{opt}	1	0,0445	< 0,001	
T_{min}	0,00	0,9863	1,000	
T_{opt}	18,92	0,6502	< 0,001	0,95
T_{max}	30,00	1,8601	< 0,001	
N	1,27	0,5343	< 0,001	

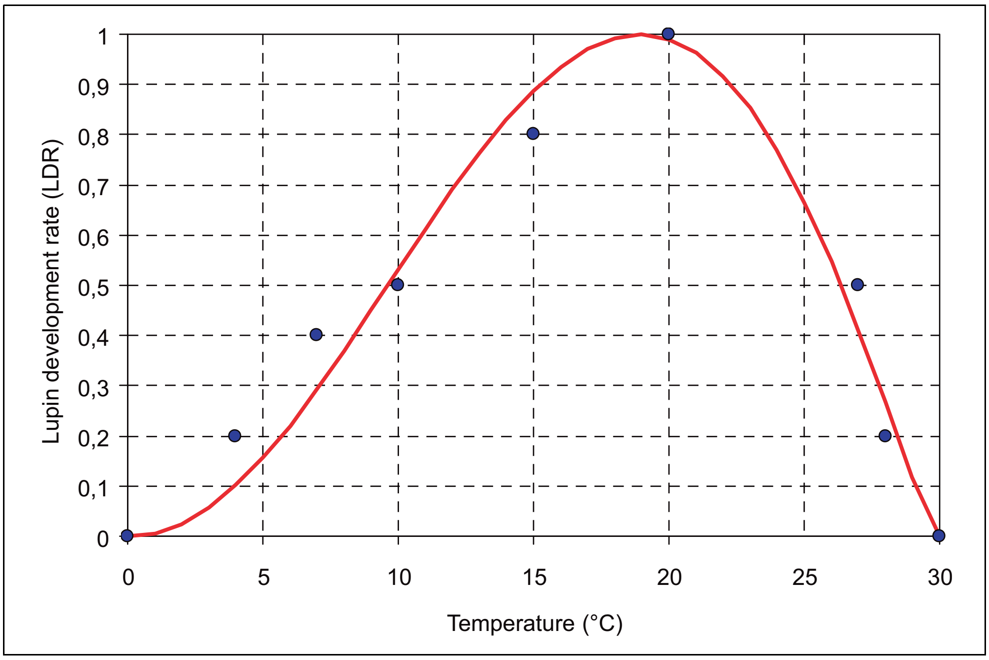

Fig. 1. Lupin development rate (LDR) depending on the temperature. (● Transformed data from DRACUP and KIRBY, 1993; FARRÉ et al., 2004. — Interpolated Beta-Hau function).

Simulation of BBCH growth stages of lupin

A data set of more than 900 BBCH field surveys (from 180 data series) collected by members of the Governmental Crop protection services and the seed breeders during the years 1996 to 2006 was used as basis for model development (Tab. 2).

The nearest located weather station was assigned to each trial site and for each BBCH observation a sum of LDR beginning from sowing date was calculated (Tab. 3, Fig. 2).

The BBCH growth stages were modelled with a logistic interpolation (Fig. 3) as follows:

[3] BBCH x = 1/1 + EXP [−(a + b Σ LDR)]

Where:
BBCH x = Predicted BBCH growth stage
a and b = Equation parameters
Σ LDR = Sum of the lupin development rate from sowing to BBCH x

The parameters of the equation for the three SIMONTO-Lupin models are summarised in Tab. 4.

Model validation

A comprehensive model validation was carried out for *L. angustifolius* (for the two other species more data were necessary).

Tab. 2. Data set used for the SIMONTO-Lupin development

Lupin Species	Region	Year	n. Trial/Year	n. of Observation
L. angustifolius	Brandenburg	2000–2003	1	16
	Saxony-Anhalt	2001–2004	3	417
	Thuringia	2002	3	151
	West Pomerania	2000–2007	3	18
L. luteus	Brandenburg	1996–2002	1	49
	Saxony-Anhalt	2001–2006	3	30
	West Pomerania	1998–2007	2	60
L. albus	Brandenburg	1996–1997	1	11
	Saxony	1997	1	9
	Saxony-Anhalt	2001–2003	2	105
	Thuringia	2002	2	41
	West Pomerania	1997	1	3

Tab. 3. Sum of the lupin development rate (LDR) between BBCH 0 to 9, 61, 69 and 87 differentiated for *L. angustifolius*, *L. luteus* and *L. albus*

Lupin Species	BBCH	n	Minimum	Maximum	Median	Mean
L. angustifolius	9	112	3.55	8.94	7.04	6.70
	61	126	35.17	53.05	41.17	41.35
	69	121	46.15	70.84	55.32	56.30
	87	112	65.67	109.83	91.29	90.83
L. luteus	9	16	3.29	11.93	7.38	7.56
	61	9	45.47	59.18	51.04	51.36
	69	7	53.45	69.65	68.37	63.80
	87	2	94.68	98.15	96.41	96.41
L. albus	9	25	4.85	9.94	7.98	7.88
	61	30	34.83	44.36	40.47	39.96
	69	30	51.52	78.49	67.73	65.55
	87	30	95.92	112.59	112.16	109.04

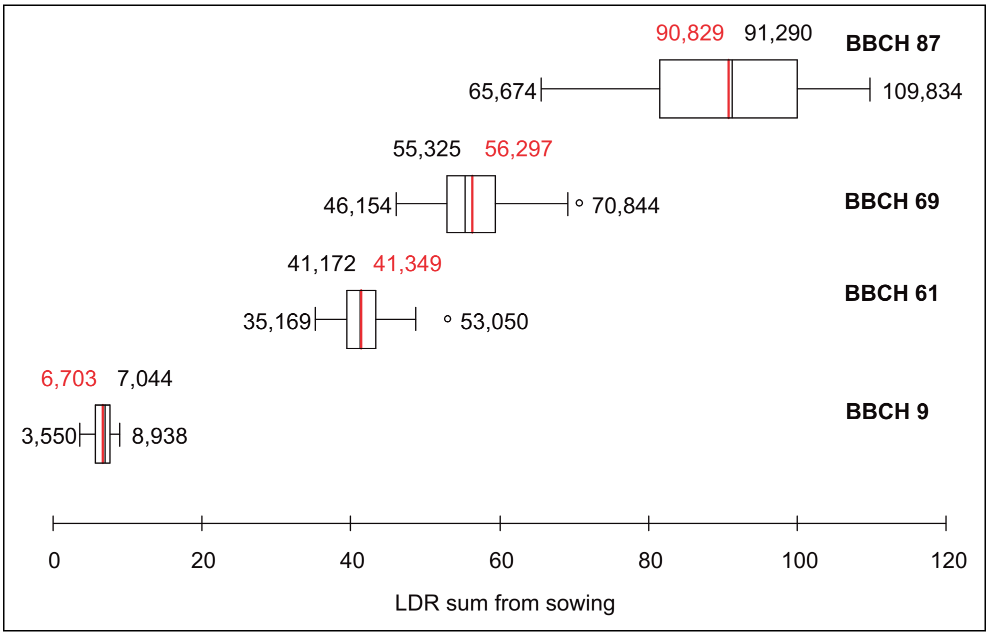

Fig. 2. Example of the variability of the sum of the lupin development rate (LDR) for BBCH growth stages 9, 61, 69 and 87 for *L. angustifolius* (data sets from Tab. 2).

For model validation three different methods were used (Racca et al., 2010).

- Subjective validation
- Statistical validation with regression analysis
- Evaluation of the deviation in days (difference between the date of the observed BBCH stage in field and the simulated date)

Subjective validation
For this type of validation the simulated progress of ontogenesis was compared manually with the monitored BBCH in field. If there was no or only minor differences between model and data collected, the prognosis was "correct" (Fig. 4A). If the monitored results (points) were below/above the simulated curve, the model had overestimated/underestimated (Fig. 4B+C). The degree of differences between model data and field data is subjective and is determined by the person who carries out the validation (Racca et al., 2010).

In total 215 data sets were analysed by this validation method. 88.4% of the records were simulated correctly, 9.8% were underestimated and 1.9% overestimated.

Statistical validation with regression analysis
For the statistical validation the model output (dependant variable) was compared to the field data (independent variable) with the help of a linear regression analysis. For each linear regression the null hypothesis (a = 0, slope b = 1) was verified by a Students t-test.

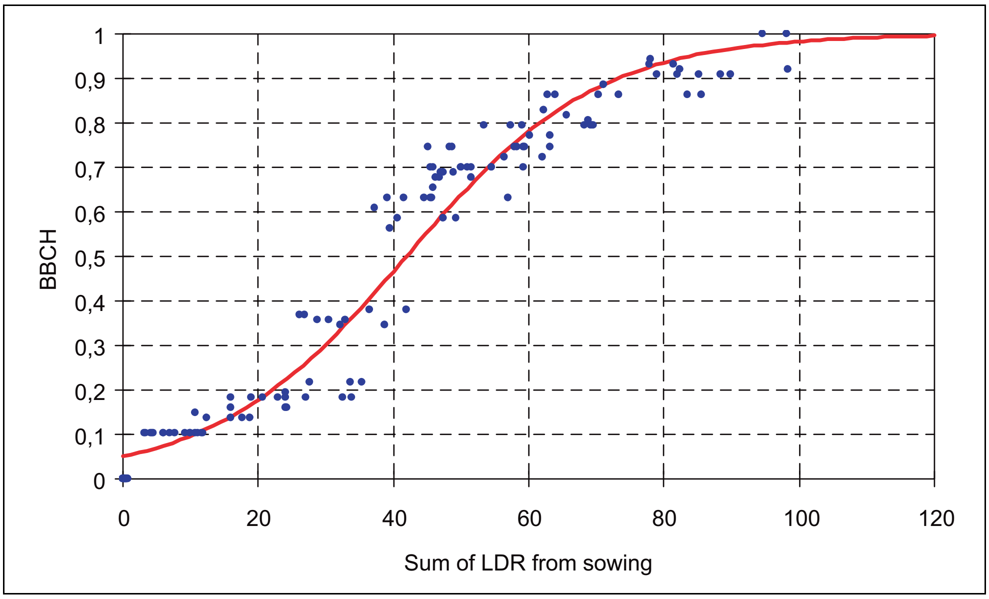

Fig. 3. Example of SIMONTO-Lupine: logistic interpolation between the BBCH recorded data and the sum of LDR from sowing for *L. luteus* (● BBCH recorded data, — Interpolating logistic function).

Tab. 4. Parameters of the three SIMONTO-Lupin models

SIMONTO-Lupin	Parameters		p	r^2
L. angustifolius	a	–3,109	< 0,001	0,88
	b	0,088	< 0,001	
L. luteus	a	–2,939	< 0,001	0,81
	b	0,070	< 0,001	
L. albus	a	–2,765	< 0,001	0,87
	b	0,075	< 0,001	

In total 229 data sets were analysed by this validation method. The average of the coefficient of determination was 0.984 and the slope b was in all cases not significant, which means that there are no significant differences between field data and simulation. All results of the statistical validation are summarized in Tab. 5.

Evaluation of the deviation in days

Unfortunately, BBCH growth stages are not strictly arithmetically dependent. Some stages can appear very early in the season and stay constant for a long period of time. The arithmetic difference between two BBCH growth stages may be small but the difference in days between the appearance of two consecutive stages may be considerable. For this validation the difference in days between the ontogenesis in field and the simulated ontogenesis was calculated. If the difference between the both dates was ±7 days the prognosis was rated "correct". Otherwise the prognosis was pointed out as "too early" or "too late" (Fig. 5).

In total 229 data sets were analysed by this validation method for two BBCH-stages: Start of flowering (BBCH 61) and end of flowering (BBCH 69).

BBCH 61 achieved a hit rate of 86.0% correct forecasts and 14.0% of the dates were simulated too late. BBCH 69 was simulated correctly in 75.5% of all cases, 22.7% of the simulations were too early and 1.7% too late.

The validation of the developed model SIMONTO-Lupin gives very satisfactory results.

Discussion

Most of the ontogenetic models (MIRSCHEL et al., 1993; WERNECKE and CLAUS, 1996; ROSSI et al., 1997; FALKE et al., 2006, 2008; ROSSBERG et al., 2005) do not consider soil, water and nutrient availability as a limiting factor and

Tab. 5. ***L. angustifolius*: Results of regression analysis of the SIMONTO-Lupin model (n = 215)**

Parameter	Minimum	Maximum	Median	Mean	Sign. a and b
r^2	0,954	0,996	0,985	0,984	
a	–1,093	3,050	0,845	0,881	
b	0,874	1,094	0,975	0,974	
(a) Pr [t]	0,266	0,998	0,833	0,807	100% s
(b) Pr [t]	0,000	0,016	0,001	0,001	100% ns

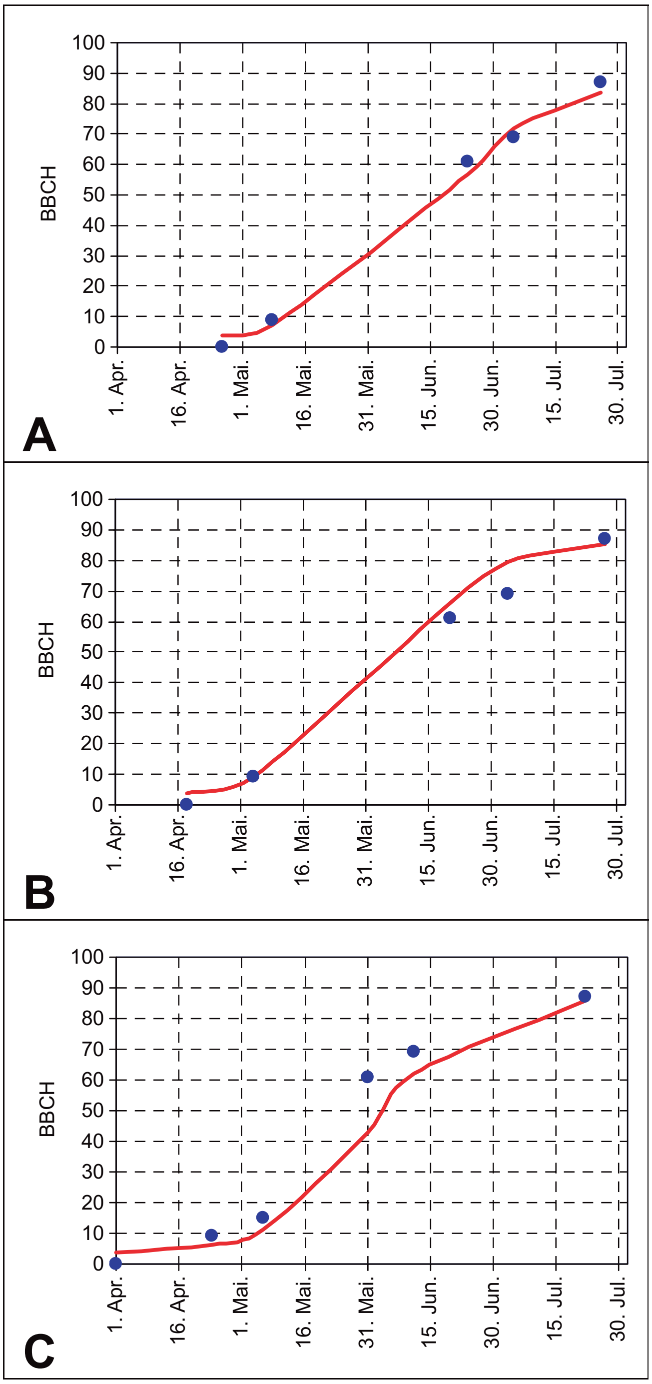

Fig. 4. *L. angustifolius*: Result of the subjective validation – Subjective comparison between the simulated (line) and the observed BBCH in field (points).
A: weather station Burkersdorf (Thuringia), year 2006 variety Idefix, classified as correct prognosis;
B: weather station Artern (Saxony-Anhalt), year 2006, variety Idefix, classified as overestimated prognosis;
C: weather station Dornburg (Thuringia), year 2008, variety Arabella, classified as underestimated prognosis.

simulate the plant development only depending on the temperature and the day length. A correlation between the different growth stages and the sum of the temperature or combination with temperature and photoperiod was done.

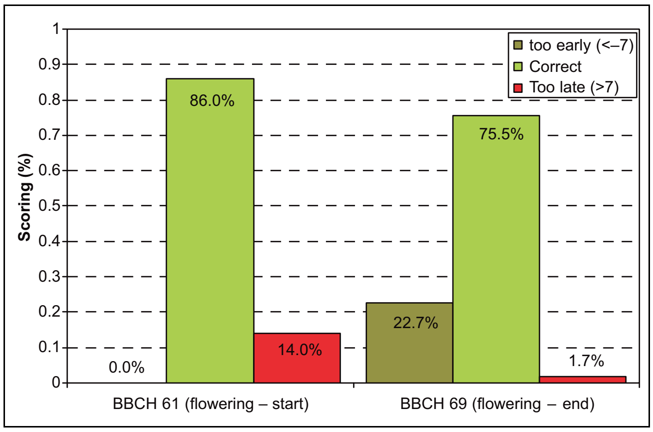

Fig. 5. *L. angustifolius*: Evaluation of the deviation in days between the date of the BBCH stage observed in field and the simulated for the start (BBCH 61) and the end (BBCH 69) of the flowering (n = 229).

The lupin growing areas in Germany are located mainly on the north-eastern part, the growing season is short with sowing time concentrated at the end of March and harvest at the beginning of August. On the assumption that day length during the growing season in this area varies from 13–14 hours in spring to 16–17 in summer, the photoperiod was also considered as a no-limiting factor. The temperature was the only parameter included in SIMONTO-Lupin model.

The appearance of phenological stages also helps to identify precisely the beginning and end of stages most sensitive to fungal diseases. In particular, the model has its practical application in conjunction with the model SIMCOL for the integrated plant disease management of the anthracnose (Racca and Tschöpe, 2010).

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