A linked process-based model to study the interaction between *Puccinia striiformis* and wheat

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Abstract

Stripe rust can cause significant losses to the wheat industry in southern Australia. There have been very few attempts to develop process-based models linking life cycles of a pathogen and its host and much of the research in crop modelling to date has focussed on providing yield estimates in the absence of diseases. Modelling provides a logical framework to incorporate quantitative relationships between the host, pathogen and the environment to help formulate disease management strategies and assist in tactical decision-making for disease control. We have developed a process-based linked wheat-*Puccinia striiformis* model and compared the predicted yield with that from field studies.

Media summary

Development of a model to investigate the impact of a pathogen on its host crop.

Key Words

Host-pathogen model, stripe rust, *Puccinia striiformis*

Introduction

Despite significant research investments, the three rusts, stem rust (*Puccinia graminis* f.sp. *tritici*), leaf rust (*Puccinia triticina*) and stripe rust (*Puccinia striiformis* f.sp. *tritici*) inflict serious losses to the Australian wheat crop each year and stripe rust alone costs $180 million (Brennan and Murray, 1998). Yield losses can be as much as 84% when no fungicide is used on susceptible varieties (Ellison and Murray 1992). *P.?striiformis tritici* (PST) on wheat does not have a sexual stage, does not require an alternate host to complete its life cycle and it produces one functional spore form, the urediospore. Some grasses and volunteer wheat growing over summer serve as inoculum reservoirs for the wheat infective form to initiate epidemics in the wheat crop. Large quantities of urediospores are produced on the leaf (Emge et al*.* 1975) which appear as yellow stripes and cause secondary cycles of infection under suitable weather conditions. A reduction in the number of kernels per head and the mass of the kernels cause yield loss (Murray et al*.* 1995) and both the length of the epidemic and the proportion of leaf area affected influence yield loss (Murray et al*.* 1994). This paper describes the development of a process-based linked wheat-PST model and its prediction success by comparing model outputs with actual field data.

Methods

Modelling environment

We have used the Dymex modelling software (Maywald et al*.* 2000) that is similar to other graphical simulation systems such as Stella (HPS Inc.) and Simulink (The Mathworks Inc.). Since it was developed for biological systems, it has a number of predefined functions that are specific to model biological relationships. The software consists of a graphical interface, the *Model Builder*, where the various inputs, processes, life stages and lifecycles are created by linking modules of the required type; and the *Model Simulator,* which runs the model using specified initialisation parameters, data and output. Dymex uses the cohort for the number of individuals in each stage of a lifecycle. In the wheat-PST model a single wheat plant is sown and a single spore initialised on each simulation day using deterministic processes and the interaction occurs on a per hectare basis where the seeding and germination rates are used to determine the leaf area available for infection.

Wheat Lifecycle

The wheat lifecycle was based on a Fortran model developed for northwest Victoria (O'Leary and Connor 1996). The nine-layer soil water module was reduced to one layer and the planting date function was updated to include latitudes north of 30?S (Hammer et al. 1987). In Dymex, the state variables are calculated for a cohort. The Fortran model simulates the crop phenology from germinated seed to anthesis, and from germinated seed to stem extension to booting. To achieve this in the Dymex version, an extra wheat plant was created (the whole cohort) at the appropriate time to track the development to booting (Fig. 1), while the first plant was tracked through the other stages.

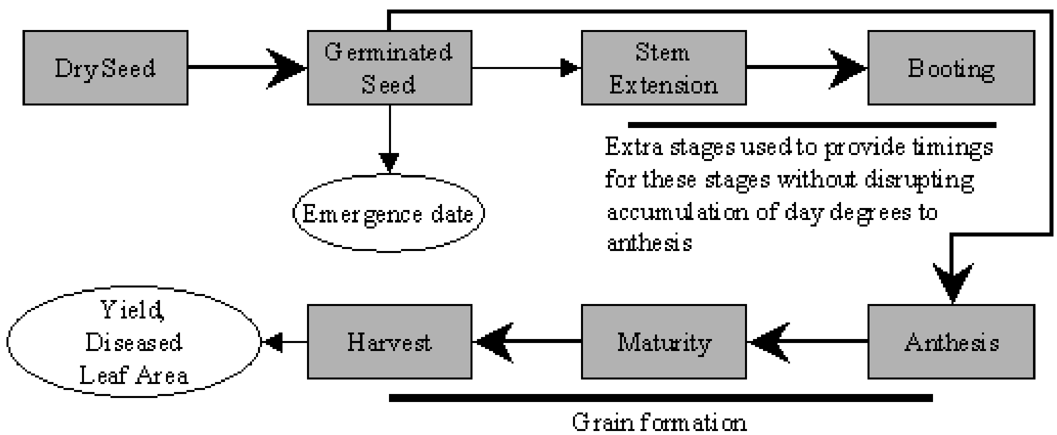

Figure 1. The Dymex wheat life cycle model.

Stripe Rust Lifecycle

The PST life cycle was developed in Dymex from ideas presented at a Modelling Workshop (Sutherst 2000). Three stages were considered, spore, infective and lesion and validated against studies from Wagga Wagga (35.17?S 147.45?E) (Ellison and Murray 1992; Murray et al. 1994), where wheat cultivars with a range of stripe rust resistance were grown over four seasons (1984-1987). Spore mortality was linked to heat and cold stress in addition to a constant daily mortality of approximately 50%. In addition, mortality is imposed on spores based on the availability of uninfected leaf area. Transfer to the infective stage occurred when daily rainfall was 1.6 mm. Surviving spores become infective and undergo a period of development to simulate penetration of the leaf surface in response to daily temperature using a linear above threshold (5?C) function with a 0.2 per degree slope. When the development was complete, the spores transferred to the lesion stage. Mortality was affected by mean relative humidity as a linear below threshold function (70% minimum Rh, slope –0.1) and the disease resistance (DR) of the wheat cultivar. DR was entered as a rating from 1 – highly resistant to 5 – susceptible. The value of DR was modified using a three-segment linear function such that it acts as a mortality factor (Rm) in a product-complement equation where the number surviving to the next time period, N_{t+1}, is N_{t+1}?=?$N_{t?}$*?1?–?(1?–?Rm), see Table 1.

Lesion mortality was caused by leaf senescence and harvesting. Lesion growth occurred at a predefined rate based on the resistance of the cultivar (Lou and Zeng 1995) and was inhibited by lack of uninfected leaf area. Spore production was 200 uredospores per mm^2 of lesion area per day, for a period of up to 12 days (Emge et al. 1975). Lesion growth is also inhibited by the mortality factor, Rm, such that the increase in lesion area is reduced by 50% of the complement (1-Rm), see Table 1.

Table 1. Mortality of spores and lesion inhibition according to disease resistance categories.

Resistance category	Disease Resistance (DR)	Rm	Mortality of spores	Lesion inhibition
Complete resistance	0	1	1.000	0.00
Resistant (R)	1	0.910	0.910	0.04
Moderately resistant (MR)	2	0.890	0.890	0.06
Moderately susceptible (MS)	3	0.865	0.865	0.07
Very susceptible (VS)	4	0.820	0.820	0.09
Susceptible (S)	5	0.150	0.150	0.43

Leaf area (cm^2) was calculated by multiplying the shoot biomass with the specific leaf area. Leaf and lesion areas were linked through feedbacks that limit lesion growth and reduce the transpiration efficiency of the plant. Thus, lesion growth had a direct impact on wheat biomass and yield. The effect on transpiration efficiency is inversely proportional to the proportion of leaf area diseased.

Results and Discussion

Four simulations were performed for Wagga Wagga (Table 2) in the absence of disease. The underestimation of yield by 10-12% may be due to the simplified water balance model used in the Dymex version.

Table 2. Yield predictions using the Fortran (Oleary3) and Dymex models in the absence of disease. Daily rainfall, mean relative humidity, maximum and minimum temperature and

	Yield (t/ha)		
Year	Oleary3	Dymex	Accuracy (Dymex/Oleary3)
1985	5.60	5.08	90.7%
1986	5.60	4.93	88.0%
1987	5.45	4.82	88.4%

Simulations were undertaken to estimate the amount of diseased leaf area and compare these with field data (Table 3). Similar weather and disease resistance measures to that given in Ellison and Murray (1992) were used for each year and the relationship between the disease resistance parameter, DR, and the mortality factor, Rm, was developed mainly from the 1984 data. The estimation of leaf area affected shows two important features: an increase in the leaf area affected with decreasing resistance and year to year variation that is at least consistent with the field trials.

Table 3. Comparison of stripe rust severity on different varieties at Wagga Wagga in 1984 (Ellison and Murray 1992) and the Dymex model developed using the variety Matong.

		Stripe rust (% leaf area)							
		1984		1985		1986		1987	
Resistance[3]	DR[4]	Field[1]	Model[2]	Field	Model	Field	Model	Field	Model
R	1	17	6	0	4	0	11	0	2
MR	2	25	19	0	9	0	21		3
MS	3	17	38	0	18		28	1	5
S	4	30	48	0	25	8	31	4	6
VS	5	73-82	76	4	40	1	33	1	14

1 - Leaf area affected assessed at early milk stage. 2 - The maximum recorded Leaf area affected. 3 - Adult plant reaction for the varieties used in field trials. 4 - Value of the disease resistance parameter in the Dymex model

The agreement between model and the field data on yield was consistent within an order of magnitude or better. However, the prediction of yield for 1987 was poor and at the upper end of the range for the field data (Table 4), partly because yield is strongly influenced by various cultivar specific parameters that were held constant in the simulations.

This study demonstrated that the Dymex modelling software could successfully be used for a process-based modelling of the wheat-PST host-pathogen system. The pathogen lifecycle and its interaction with the host plant can be easily coded in Fortran or C to be a part of the more elaborate farming systems model APSIM (McCown et al. 1996) and this approach is under development (Manschadi et al. this vol). To be truly representative of the cropping systems in place throughout the wheat belt it would be necessary to compile a set of phenological attributes for each of the cultivars to better integrate and model host-pathogen interactions.

Table 4. Comparison of actual yield reductions due to stripe rust at field trials in Wagga Wagga (Ellison and Murray 1992) and the predicted yield from the Dymex model .

	Percentage reduction in yield.[2]			
	1984	1985	1986	1987

Resistance	DR	Field	Model	Field	Model	Field	Model	Field	Model
R	1	9	3	-3	2	5	4	10	0
MR	2	21	9	-6	4	13	7		1
MS	3	15	20	-3	7		8	-4	1
S	4	28	29	6	10	9-14	8	-9	2
VS	5	51-75	52	17	19	23	10	12	7
	Yield (t/ha)[1]	3.3-4.5	4.9	4.2-5.8	4.9	3.9-4.8	5.2	2.6-2.8	5.1

1 In the field trials protection from foliar diseases was achieved by spraying with fungicides at 4-week intervals.

2 Negative values indicate an increase in yield compared to the disease-free control

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