Chapter 9. The RICEPEST and WHEATPEST Models

This chapter introduces two sibling simulation models that have been developed to simulate yield losses due to rice pests (RICEPEST) and yield losses due to wheat pests (WHEATPEST). Both models have many features in common:

- **Objectives of developing RICEPEST and WHEATPEST.** Both models were developed in order to simulate yield losses caused by pests (diseases, insects, weeds), individually or in combination, under a range of production situations. This allows (1) a ranking of the pests according to their importance in terms of the yield losses they cause in various production situations and (2) a simulation of the yield gains associated with new technologies, including plant protection methods. The results can provide a formal basis for long term strategies in crop health management, e.g., priority setting for research.
- **Conceptual framework.** Both models have been developed under the conceptual framework of GENECROP and GENEPEST described in the previous chapters, where relationships between production situations, yield levels, and damage mechanisms are formally captured into simulation models.
- **Generic structure of the models**. Both RICEPEST and WHEATPEST are built according to the same GENECROP structure, which has been described in Chapter 7 for the simulation of crop growth, and which accounts for damage mechanisms as described under GENEPEST in Chapter 8. In both the rice and the wheat systems, the system considered is 1 m^2 of crop in a field, with a time step of one day. Contrary to RICEPEST, WHEATPEST does not include a component for the dynamics of tillers, because the pests addressed in the wheat model do not entail injuries directly affecting tillers.

The purpose of this chapter is to introduce the reader to models that account for multiple injuries. The way these models behave with varying levels of differing injuries is shown later with the simulation models. The details of the models are not discussed, but the reader will find full listings of the programs in Appendices 9.1 and 9.2, as well as references.

Damage mechanisms for a set of pests in rice

The different rice pests addressed and the mechanisms are summarized in Table 9.1. The details of the inclusion of these damage mechanisms in RICEPEST can be found in Willocquet et al. (1998, 2000, 2002, 2004), and are implemented in the RICEPEST.STMX file.

Table 9.1. Rice pests addressed, their damage mechanisms, and their effect in RICEPEST

Rice pest	Damage mechanism[a]	Physiological effect	Effect in RICEPEST
Bacterial leaf blight (BLB)	Light stealer	Reduces the intercepted radiation	Reduces the green LAI
Leaf blast (LB)	Light stealer Leaf senescence accelerator Assimilate sapper	Reduces the intercepted radiation Increases leaf senescence Removes soluble assimilates from host	Reduces the green LAI (lesion area + virtual lesion area) Reduces the biomass of leaves by increasing the rate of leaf senescence Outflows assimilates from the pool of assimilates
Sheath blight (SHB)	Light stealer Leaf senescence accelerator	Reduces the intercepted radiation Increases leaf senescence	Reduces the green LAI Reduces the biomass of leaves by increasing the rate of leaf senescence
Brown spot (BS)	Light stealer	Reduces the intercepted radiation	Reduces the green LAI (lesion area + virtual lesion area)
Tungro (TUNGRO)	Photosynthetic rate reducer	Disrupts phloem transport And reduces the rate of carbon uptake	Reduces the RUE
Neck blast (NB)	Tissue consumer	Disrupts transport of carbohydrates towards panicles	Reduces the flow of assimilates towards panicles
Sheath rot (SHR)	Tissue consumer	Disrupts panicle emergence	Reduces the flow of assimilates towards panicles
White head (WH)	Assimilate sapper	Disrupts transport of carbohydrates towards panicles	Reduces the flow of assimilates towards panicles
Weeds (WEED)	Photosynthetic rate reducer	Reduces water and nutrient supply Light stealer Reduction of water, nutrient and radiation reduces RUE	Reduces the RUE
Dead hearts(DH)	Stand reducer	Reduces the number and biomass of tillers	Reduces the number of vegetative tillers
Brown plant-hoppers (BPH)	Assimilate sapper Leaf senescence accelerator	Removes soluble assimilates from host Increases leaf senescence	Outflows assimilates from the pool of assimilates Reduces the biomass of leaves by increasing the rate of leaf senescence
Defoliators (DEF)	Tissue consumer	Reduces leaf biomass	Reduces the biomass of leaves by increasing the rate of leaf senescence

Derived from Rabbinge and Vereyken (1980), Rabbinge and Rijsdijk (1981) and Boote et al. (1983).

Damage mechanisms for a set of pests in wheat

The different wheat pests addressed and the mechanisms are summarized in Table 9.2. The details of the inclusion of these damage mechanisms in WHEATPEST can be found in Willocquet et al. (2008), and are implemented in the WHEATPEST.STMX file.

Table 9.2. Wheat pests addressed, their damage mechanisms, and their effect in WHEATPEST

Wheat pest	**Damage mechanism**[a]	**Physiological effect**	**Effect in WHEATPEST**
Powdery mildew (PM)	Light stealer	Reduces the intercepted radiation	Reduces the green LAI (lesion area + virtual lesion area)
Yellow rust (YR)	Light stealer Assimilate sapper	Reduces the intercepted radiation Removes soluble assimilates from host	Reduces the green LAI (lesion area + virtual lesion area) Outflows assimilates from the pool of assimilates
Brown rust (BR)	Light stealer Assimilate sapper	Reduces the intercepted radiation Removes soluble assimilates from host	Reduces the green LAI Outflows assimilates from the pool of assimilates
Septoria nodorum Blotch (SNB)	Light stealer Assimilate sapper	Reduces the intercepted radiation Removes soluble assimilates from host	Reduces the green LAI Outflows assimilates from the pool of assimilates
Septoria tritici Blotch (STB)	Light stealer Assimilate sapper	Reduces the intercepted radiation Removes soluble assimilates from host	Reduces the green LAI (lesion area + virtual lesion area) Outflows assimilates from the pool of assimilates
Take all (TAK)	Photosynthetic rate reducer	Disrupts nitrogen and water uptake	Reduces the RUE
Eyespot (EYS)	Photosynthetic rate reducer	Disrupts nitrogen and water uptake	Reduces the RUE
Sharp eyespot (SHY)	Photosynthetic rate reducer	Disrupts nitrogen and water uptake	Reduces the RUE
Fusarium stem rot (FST)	Photosynthetic rate reducer	Disrupts nitrogen and water uptake	Reduces the RUE
BYDV	Photosynthetic rate reducer	Disrupts phloem transport Reduces the rate of carbon uptake	Reduces the RUE

Fusarium Head Blight (FHB)	Tissue consumer[b]	Disrupts transport of carbohydrates towards ears.	Reduces the flow of assimilates towards ears
Weeds (WEED)	Photosynthetic rate reducer	Reduces water and nutrient supply Light stealer Reduction of water, nutrient and radiation reduces RUE	Reduces the RUE
Aphids (APH)	Assimilate sapper Photosynthetic rate reducer	Removes soluble assimilates from host Reduces the RUE	Outflows assimilates from the pool of assimilates Reduces the RUE

[a] Derived from Rabbinge & Vereyken (1980), Rabbinge & Rijsdijk (1981) and Boote et al. (1983).
[b] Production of toxins not included.

Weather and injury drivers in RICEPEST and WHEATPEST

Weather

RICEPEST uses constant daily minimum temperature, maximum temperature and radiation of 24°C, 30°C, and 17 MJ/m^2, respectively. These are within the range of weather values during the rainy season in tropical Asia.

For WHEATPEST, monthly averages of daily temperature and radiation, computed from weather in Wageningen (The Netherlands) during 1951-1980 (Spitters et al., 1989), are interpolated in order to generate daily temperature and radiation.

Injury drivers

Injuries were not entered in the models as random variables; rather, patterns of injuries are used, which correspond to specific production situations for both rice in tropical Asia (Savary et al., 2000; 2006), and wheat in Western Europe (Polley and Thomas, 1991; Daamen, 1990; Daamen and Stol, 1990, 1992, 1994; Daamen et al., 1989, 1991, 1992). This linkage between production situations and patterns of injuries has been shown to be both reliable and dynamic as production situations evolve (Savary et al. 2006). In turn, the intrinsic rate of (attainable) growth was made dependent on production situations. This was, again, made possible through careful field surveys where yields were measured, experiments, data published in the literature, and a combination of these sources. Thus, the injury drivers actually represent a linkage between production situations – attainable yield – intrinsic crop growth – injury patterns.

Simulations with RICEPEST and WHEATPEST

The STELLA models RICEPEST.STMX and WHEATPEST.STMX will allow you, for rice and wheat, respectively, to:

- explore the model structure and equations,
- explore the model inputs for attainable growth
- explore the model inputs for actual growth, i.e. the driving functions of the different pests included
- run the model with varying levels of pest inputs, which will allow you to explore:
    - the effects of individual injuries on crop growth and yield
    - the effects of combined injuries on crop growth and yield

Summary

This chapter describes:

- A formal modeling structure which captures the linkages between production situations – attainable yield – intrinsic crop growth – injury patterns.
- The framework and objectives under which RICEPEST and WHEATPEST have been developed.
- The damage mechanisms associated with rice and wheat pests and how the corresponding (multiple) injuries are captured into RICEPEST and WHEATPEST.
- Includes the STELLA files, which can be used to explore the models structures, and the effect of injuries, individually or in combination, on the simulated dynamics of rice and wheat crop growth.

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Appendix 9.1. Program listing of RICEPEST

```
LeafW(t) = LeafW(t - dt) + (PartL - RSenL) * dt
INIT LeafW = 10
INFLOWS:
PartL = CPL*(Pool-rdiv)
OUTFLOWS:
RSenL = ((rrsen+(SenSHB*SHB)+(SenLB*LB)+DEF)*LeafW)+RDHL+(senBPH*rdBPH)
maxst(t) = maxst(t - dt) + (partScopy) * dt
INIT maxst = 6
INFLOWS:
partScopy = PartS
PanW(t) = PanW(t - dt) + (PartP + RTransloc - inj_pan) * dt
INIT PanW = 0
INFLOWS:
PartP = CPP*(Pool-rdiv)
```

RTransloc = IF(DVS>1) then DDIST else 0

OUTFLOWS:

inj_pan = (PartP+RTransloc)*(NB+SHR+WH-(NB*SHR)-(NB*WH)-(SHR*WH)-(NB*SHR*WH))

Pool(t) = Pool(t - dt) + (RGrowth - PartS - PartL - PartP - PartR - rdiv) * dt

INIT Pool = 0

INFLOWS:

RGrowth = RAD*RUE*(1-EXP(-k*LAI))*(1-(1-exp(-0.003*WEED)))*(1-(0.7*Virdis))*pRUE

OUTFLOWS:

PartS = CPS*(Pool-rdiv)

PartL = CPL*(Pool-rdiv)

PartP = CPP*(Pool-rdiv)

PartR = CPR*(Pool-rdiv)

rdiv = (rsuck*BPH)+(LB*LAI*LBspoDW)

REPTIL(t) = REPTIL(t - dt) + (Rmat - Rmortr) * dt

INIT REPTIL = 0

INFLOWS:

Rmat = if DVS<0.8 or DVS>1 then 0 else if VTIL<FST*Totil then 0 else RRMAT*VTIL

OUTFLOWS:

Rmortr = rrmort*REPTIL

RootW(t) = RootW(t - dt) + (PartR) * dt

INIT RootW = 5

INFLOWS:

PartR = CPR*(Pool-rdiv)

SDEFn(t) = SDEFn(t - dt) + (RDEF) * dt

INIT SDEFn = 0

INFLOWS:

RDEF = DEFn

SDHn(t) = SDHn(t - dt) + (RDH) * dt

INIT SDHn = 0

INFLOWS:

RDH = DHn

STEMP(t) = STEMP(t - dt) + (Dtemp) * dt

INIT STEMP = 320

INFLOWS:

Dtemp = ((TMAX+TMIN)/2)-TBASE

StemW(t) = StemW(t - dt) + (PartS - RTransloc - RsenST) * dt

INIT StemW = 6

INFLOWS:

PartS = CPS*(Pool-rdiv)

OUTFLOWS:

RTransloc = IF(DVS>1) then DDIST else 0

RsenST = RDHST

VTIL(t) = VTIL(t - dt) + (Rtil - Rmat - Rmrtv) * dt

INIT VTIL = 250

INFLOWS:

Rtil = PartLS*STW*(1-(VTIL/Maxtil))*DVE

OUTFLOWS:

Rmat = if DVS<0.8 or DVS>1 then 0 else if VTIL<FST*Totil then 0 else RRMAT*VTIL

Rmrtv = (rrmort*VTIL)+DH

BetaBS = 6.3

BetaLB = 3

BLB = pBLB*BLBn

BLBn = GRAPH(TIME)

(0.00, 0.00), (24.0, 0.00), (48.0, 0.00), (72.0, 0.005), (96.0, 0.01), (120, 0.00)

BPH = pBPH*BPHn

BPHn = GRAPH(TIME)

(0.00, 0.00), (10.0, 0.00), (20.0, 0.00), (30.0, 0.00), (40.0, 60.0), (50.0, 125), (60.0, 190), (70.0, 250), (80.0, 250), (90.0, 145), (100, 65.0), (110, 0.00), (120, 0.00)

BS = pBS*BSn

BSn = GRAPH(TIME)

(0.00, 0.00), (24.0, 0.00), (48.0, 0.00), (72.0, 0.005), (96.0, 0.01), (120, 0.01)

CPL = CPPL*(1-CPR)

CPP = CPPP*(1-CPR)

CPPL = GRAPH(DVS)

(0.00, 0.55), (0.1, 0.536), (0.2, 0.521), (0.3, 0.507), (0.4, 0.493), (0.5, 0.479), (0.6, 0.464), (0.7, 0.45), (0.8, 0.3), (0.9, 0.15), (1, 0.00), (1.10, 0.00), (1.20, 0.00), (1.30, 0.00), (1.40, 0.00), (1.50, 0.00), (1.60, 0.00), (1.70, 0.00), (1.80, 0.00), (1.90, 0.00), (2.00, 0.00)

CPPP = GRAPH(DVS)

(0.00, 0.00), (0.05, 0.00), (0.1, 0.00), (0.15, 0.00), (0.2, 0.00), (0.25, 0.00), (0.3, 0.00), (0.35, 0.00), (0.4, 0.00), (0.45, 0.00), (0.5, 0.00), (0.55, 0.00), (0.6, 0.00), (0.65, 0.00), (0.7, 0.00), (0.75, 0.00), (0.8, 0.143), (0.85, 0.286), (0.9, 0.429), (0.95, 0.571), (1.00, 0.714), (1.05, 0.857), (1.10, 1.00), (1.15, 1.00), (1.20, 1.00), (1.25, 1.00), (1.30, 1.00), (1.35, 1.00), (1.40, 1.00), (1.45, 1.00), (1.50, 1.00), (1.55, 1.00), (1.60, 1.00), (1.65, 1.00), (1.70, 1.00), (1.75, 1.00), (1.80, 1.00), (1.85, 1.00), (1.90, 1.00), (1.95, 1.00), (2.00, 1.00)

CPR = GRAPH(DVS)

(0.00, 0.3), (0.1, 0.263), (0.2, 0.225), (0.3, 0.188), (0.4, 0.15), (0.5, 0.112), (0.6, 0.075), (0.7, 0.038), (0.8, 0.00), (0.9, 0.00), (1, 0.00), (1.10, 0.00), (1.20, 0.00), (1.30, 0.00), (1.40, 0.00), (1.50, 0.00), (1.60, 0.00), (1.70, 0.00), (1.80, 0.00), (1.90, 0.00), (2.00, 0.00)

CPS = (1-CPL-CPP)*(1-CPR)

cumul%DH = 100*SDHn/Totil

DACE = TIME+14

dBPHDWn = GRAPH(TIME)

(0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00), (13.0, 0.00), (14.0, 0.00), (15.0, 0.00), (16.0, 0.00), (17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00), (21.0, 0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00), (26.0, 0.00), (27.0, 0.00), (28.0, 0.00), (29.0, 0.00), (30.0, 0.0125), (31.0, 0.0125), (32.0, 0.0125), (33.0, 0.0125), (34.0, 0.0125), (35.0, 0.0125), (36.0, 0.0125), (37.0, 0.0125), (38.0, 0.0125), (39.0, 0.0125), (40.0, 0.0125), (41.0, 0.0125), (42.0, 0.0125), (43.0, 0.0125), (44.0, 0.0125), (45.0, 0.0125), (46.0, 0.0125), (47.0, 0.0125), (48.0, 0.0125), (49.0, 0.0125), (50.0, 0.0125), (51.0, 0.0125), (52.0, 0.0125), (53.0, 0.0125), (54.0, 0.0125), (55.0, 0.0125), (56.0, 0.0125), (57.0, 0.0125), (58.0, 0.0125), (59.0, 0.0125), (60.0, 0.0125), (61.0, 0.0125), (62.0, 0.0125), (63.0, 0.0125), (64.0, 0.0125), (65.0, 0.0125), (66.0, 0.0125), (67.0, 0.0125), (68.0, 0.0125), (69.0, 0.0125), (70.0, 0.0125), (71.0, 0.00), (72.0, 0.00), (73.0, 0.00), (74.0, 0.00), (75.0, 0.00), (76.0, 0.00), (77.0, 0.00), (78.0, 0.00), (79.0, 0.00), (80.0, 0.00), (81.0, 0.00), (82.0, 0.00), (83.0, 0.00), (84.0, 0.00), (85.0, 0.00), (86.0, 0.00), (87.0, 0.00), (88.0, 0.00), (89.0, 0.00), (90.0, 0.00), (91.0, 0.00), (92.0, 0.00), (93.0, 0.00), (94.0, 0.00), (95.0, 0.00), (96.0, 0.00), (97.0, 0.00), (98.0, 0.00), (99.0, 0.00), (100, 0.00), (101, 0.00), (102, 0.00),

(103, 0.00), (104, 0.00), (105, 0.00), (106, 0.00), (107, 0.00), (108, 0.00), (109, 0.00), (110, 0.00), (111, 0.00), (112, 0.00), (113, 0.00), (114, 0.00), (115, 0.00), (116, 0.00), (117, 0.00), (118, 0.00), (119, 0.00), (120, 0.00)

ddist = 0.0067*maxst

DEF = pDEF*DEFn

DEFn = GRAPH(TIME)

(0.00, 0.00), (10.0, 0.00), (20.0, 0.00), (30.0, 0.0003), (40.0, 0.0005), (50.0, 0.0002), (60.0, 0.00), (70.0, 0.00), (80.0, 0.00), (90.0, 0.00), (100, 0.00), (110, 0.00), (120, 0.00)

DH = pDH*DHn

DHn = GRAPH(TIME)

(0.00, 0.00), (10.0, 0.00), (20.0, 0.00), (30.0, 0.00), (40.0, 0.5), (50.0, 0.00), (60.0, 0.00), (70.0, 0.00), (80.0, 0.00), (90.0, 0.00), (100, 0.00), (110, 0.00), (120, 0.00)

DVE = GRAPH(DVS)

(0.00, 1.00), (0.4, 1.00), (0.8, 0.00), (1.20, 0.00), (1.60, 0.00), (2.00, 0.00)

DVS = if stemp<TFLOW then STEMP/TFLOW ELSE 1+((STEMP-TFLOW)/(TMAT-TFLOW))

DWBPH = 0.001

FST = 0.05

grain__yield = 0.85*PanW

k = 0.6

LAI = LeafW*SLA*(1-BLB)*((1-BS)^BetaBS)*(1-SHB)*((1-LB)^BetaLB)

LB = pLB*LBn

LBn = GRAPH(TIME)

(0.00, 0.00), (5.00, 0.00), (10.0, 0.00), (15.0, 0.002), (20.0, 0.004), (25.0, 0.007), (30.0, 0.01), (35.0, 0.005), (40.0, 0.00), (45.0, 0.00), (50.0, 0.00), (55.0, 0.00), (60.0, 0.00), (65.0, 0.00), (70.0, 0.00), (75.0, 0.00), (80.0, 0.00), (85.0, 0.00), (90.0, 0.00), (95.0, 0.00), (100, 0.00), (105, 0.00), (110, 0.00), (115, 0.00), (120, 0.00)

LBspoDW = GRAPH(TIME)

(0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 20.0), (11.0, 20.0), (12.0, 20.0), (13.0, 20.0), (14.0, 20.0), (15.0, 20.0), (16.0, 20.0), (17.0, 20.0), (18.0, 20.0), (19.0, 20.0), (20.0, 20.0), (21.0, 20.0), (22.0, 20.0), (23.0, 20.0), (24.0, 20.0), (25.0, 0.00), (26.0, 0.00), (27.0, 0.00), (28.0, 0.00), (29.0, 0.00), (30.0, 0.00), (31.0, 0.00), (32.0, 0.00), (33.0, 0.00), (34.0, 0.00), (35.0, 0.00), (36.0, 0.00), (37.0, 0.00), (38.0, 0.00), (39.0, 0.00), (40.0, 0.00), (41.0, 0.00), (42.0, 0.00), (43.0, 0.00), (44.0, 0.00), (45.0,

0.00), (46.0, 0.00), (47.0, 0.00), (48.0, 0.00), (49.0, 0.00), (50.0, 0.00), (51.0, 0.00), (52.0, 0.00), (53.0, 0.00), (54.0, 0.00), (55.0, 0.00), (56.0, 0.00), (57.0, 0.00), (58.0, 0.00), (59.0, 0.00), (60.0, 0.00), (61.0, 0.00), (62.0, 0.00), (63.0, 0.00), (64.0, 0.00), (65.0, 0.00), (66.0, 0.00), (67.0, 0.00), (68.0, 0.00), (69.0, 0.00), (70.0, 0.00), (71.0, 0.00), (72.0, 0.00), (73.0, 0.00), (74.0, 0.00), (75.0, 0.00), (76.0, 0.00), (77.0, 0.00), (78.0, 0.00), (79.0, 0.00), (80.0, 0.00), (81.0, 0.00), (82.0, 0.00), (83.0, 0.00), (84.0, 0.00), (85.0, 0.00), (86.0, 0.00), (87.0, 0.00), (88.0, 0.00), (89.0, 0.00), (90.0, 0.00), (91.0, 0.00), (92.0, 0.00), (93.0, 0.00), (94.0, 0.00), (95.0, 0.00), (96.0, 0.00), (97.0, 0.00), (98.0, 0.00), (99.0, 0.00), (100, 0.00), (101, 0.00), (102, 0.00), (103, 0.00), (104, 0.00), (105, 0.00), (106, 0.00), (107, 0.00), (108, 0.00), (109, 0.00), (110, 0.00), (111, 0.00), (112, 0.00), (113, 0.00), (114, 0.00), (115, 0.00), (116, 0.00), (117, 0.00), (118, 0.00), (119, 0.00), (120, 0.00)

LWT = LeafW/VTIL

Maxtil = 900

NB = pNB*NBn

NBn = GRAPH(TIME)

(0.00, 0.01), (120, 0.01)

PartLS = PartL+PartS

pBLB = 0

pBPH = 0

pBS = 0

pDEF = 0

pDH = 0

pLB = 0

pNB = 0

pRUE = 1

pSHB = 0

pSHR = 0

pVD = 0

pWEED = 0

pWH = 0

RAD = 17

rdBPH = if DVS<1 then 0 else pBPH*dBPHDWn

RDHL = LWT*DH

RDHST = STWT*DH

RRMAT = 0.3

rrmort = GRAPH(DVS)

(0.00, 0.00), (0.1, 0.00), (0.2, 0.00), (0.3, 0.00), (0.4, 0.00), (0.5, 0.02), (0.6, 0.02), (0.7, 0.02), (0.8, 0.02), (0.9, 0.02), (1, 0.00), (1.10, 0.00), (1.20, 0.00), (1.30, 0.00), (1.40, 0.00), (1.50, 0.00), (1.60, 0.00), (1.70, 0.00), (1.80, 0.00), (1.90, 0.00), (2.00, 0.00)

rrsen = GRAPH(DVS)

(0.00, 0.00), (0.1, 0.00), (0.2, 0.00), (0.3, 0.00), (0.4, 0.00), (0.5, 0.00), (0.6, 0.00), (0.7, 0.00), (0.8, 0.00), (0.9, 0.00), (1, 0.00), (1.10, 0.013), (1.20, 0.026), (1.30, 0.04), (1.40, 0.04), (1.50, 0.04), (1.60, 0.04), (1.70, 0.04), (1.80, 0.04), (1.90, 0.04), (2.00, 0.04)

rsuck = 0.002

RUE = GRAPH(DVS)

(0.00, 1.20), (0.1, 1.20), (0.2, 1.20), (0.3, 1.20), (0.4, 1.20), (0.5, 1.20), (0.6, 1.20), (0.7, 1.20), (0.8, 1.20), (0.9, 1.20), (1, 1.15), (1.10, 1.10), (1.20, 1.10), (1.30, 1.10), (1.40, 1.10), (1.50, 1.10), (1.60, 1.10), (1.70, 1.10), (1.80, 1.10), (1.90, 1.10), (2.00, 1.10)

senBPH = 6

SenLB = 0.0378

SenSHB = 0.076

SHB = pSHB*SHBn

SHBn = GRAPH(TIME)

(0.00, 0.00), (10.0, 0.00), (20.0, 0.00), (30.0, 0.00), (40.0, 0.0023), (50.0, 0.0033), (60.0, 0.0066), (70.0, 0.01), (80.0, 0.0088), (90.0, 0.0077), (100, 0.0066), (110, 0.0066), (120, 0.0066)

SHR = pSHR*SHRn

SHRn = GRAPH(TIME)

(0.00, 0.01), (120, 0.01)

SLA = GRAPH(DVS)

(0.00, 0.037), (1.00, 0.018), (2.00, 0.017)

STW = 20

STWT = StemW/VTIL

TBASE = 8

TFLOW = 1450

TMAT = 2030

TMAX = 30

TMIN = 24

Totil = VTIL+REPTIL

Virdis = pVD*Virdisn

Virdisn = GRAPH(TIME)

(0.00, 0.00), (10.5, 0.00), (21.0, 0.00), (31.5, 0.005), (42.0, 0.01), (52.5, 0.01), (63.0, 0.01), (73.5, 0.01), (84.0, 0.01), (94.5, 0.01), (105, 0.01)

WEED = pWEED*WEEDn

WEEDn = GRAPH(TIME)

(0.00, 0.00), (10.0, 1.00), (20.0, 2.00), (30.0, 3.00), (40.0, 4.00), (50.0, 5.00), (60.0, 6.00), (70.0, 7.00), (80.0, 8.00), (90.0, 9.00), (100, 10.0), (110, 10.0), (120, 10.0)

WH = pWH*WHn

WHn = GRAPH(TIME)

(0.00, 0.01), (120, 0.01)

Appendix 9.2. Program listing of WHEATPEST

EarB(t) = EarB(t - dt) + (PartE + RTransloc - inj_ear) * dt

INIT EarB = 0

INFLOWS:

PartE = CPE*(Pool-rasdiv)

RTransloc = IF(DVS>1) then ddist else 0

OUTFLOWS:

inj_ear = (PartE+RTransloc)*(1.1*FHB)

Honey(t) = Honey(t - dt) + (rhoney) * dt

INIT Honey = 0

INFLOWS:

rhoney = 0.35*rsap

LeafB(t) = LeafB(t - dt) + (PartL - RSenL) * dt

INIT LeafB = 10

INFLOWS:

PartL = CPL*(Pool-rasdiv)

OUTFLOWS:

RSenL = rrsen*LeafB

MaxStemb(t) = MaxStemb(t - dt) + (rmaxstemb) * dt

INIT MaxStemb = 6

INFLOWS:

rmaxstemb = PartS

Pool(t) = Pool(t - dt) + (RGrowth - PartS - PartL - PartE - PartR - rasdiv) * dt

INIT Pool = 0

INFLOWS:

RGrowth = RAD*RUE*(1-EXP(-k*LAI))*(1-(0.35*BYDV))*(1-TAK)*(1-(1-exp(-0.003*WEED)))*(MAX(0,(1-(0.63*SNB))))*(MAX(0,(1-(0.63*STB))))*(1-(0.35*EYS))*(1-(0.3*SHY))*(1-(0.45*FST))*rfaph

OUTFLOWS:

PartS = CPS*(Pool-rasdiv)

PartL = CPL*(Pool-rasdiv)

PartE = CPE*(Pool-rasdiv)

PartR = CPR*(Pool-rasdiv)

rasdiv = (min(Pool,(4.62*YR*LAI)+(4.62*BR*LAI)+rsap))

RootB(t) = RootB(t - dt) + (PartR) * dt

INIT RootB = 5

INFLOWS:

PartR = CPR*(Pool-rasdiv)

StemB(t) = StemB(t - dt) + (PartS - RTransloc) * dt

INIT StemB = 6

INFLOWS:

PartS = CPS*(Pool-rasdiv)

OUTFLOWS:

RTransloc = IF(DVS>1) then ddist else 0

STEMP(t) = STEMP(t - dt) + (Dtemp) * dt

INIT STEMP = 620

INFLOWS:

Dtemp = ((TMAX+TMIN)/2)-TBASE

aphfw = APHN*sfwaph*multact

APHN = APHNn*pAPHN

APHNn = GRAPH(TIME)

(145, 0.00), (155, 25.0), (165, 50.0), (175, 70.0), (185, 125), (195, 250), (205, 0.00), (215, 0.00), (225, 0.00)

BetaPM = 2.5

BetaSTB = 1.25

BetaYR = 1.5

BR = pBR*BRn

BRn = GRAPH(TIME)

(75.0, 0.00), (100, 0.0004), (125, 0.0008), (150, 0.001), (175, 0.006), (200, 0.01), (225, 0.01)

BYDV = pBYDV*BYDVn

BYDVn = GRAPH(TIME)

(75.0, 0.01), (90.0, 0.01), (105, 0.01), (120, 0.01), (135, 0.01), (150, 0.01), (165, 0.01), (180, 0.01), (195, 0.01), (210, 0.01), (225, 0.01)

CPE = (1-CPR)*(1-CpPL-CPpS)

CPL = CPPL*(1-CPR)

CPPL = GRAPH(DVS)

(0.00, 0.65), (0.05, 0.65), (0.1, 0.65), (0.15, 0.67), (0.2, 0.69), (0.25, 0.7), (0.3, 0.66), (0.35, 0.62), (0.4, 0.58), (0.45, 0.54), (0.5, 0.5), (0.55, 0.41), (0.6, 0.32), (0.65, 0.23), (0.7, 0.15), (0.75, 0.12), (0.8, 0.09), (0.85, 0.06), (0.9, 0.04), (0.95, 0.00), (1.00, 0.00), (1.05, 0.00), (1.10, 0.00), (1.15, 0.00), (1.20, 0.00), (1.25, 0.00), (1.30, 0.00), (1.35, 0.00), (1.40, 0.00), (1.45, 0.00), (1.50, 0.00), (1.55, 0.00), (1.60, 0.00), (1.65, 0.00), (1.70, 0.00), (1.75, 0.00), (1.80, 0.00), (1.85, 0.00), (1.90, 0.00), (1.95, 0.00), (2.00, 0.00)

CPPS = GRAPH(DVS)

(0.00, 0.35), (0.05, 0.35), (0.1, 0.35), (0.15, 0.33), (0.2, 0.31), (0.25, 0.3), (0.3, 0.34), (0.35, 0.38), (0.4, 0.42), (0.45, 0.46), (0.5, 0.5), (0.55, 0.59), (0.6, 0.68), (0.65, 0.77), (0.7, 0.85), (0.75, 0.88), (0.8, 0.91), (0.85, 0.94), (0.9, 0.96), (0.95, 1.00), (1.00, 0.5), (1.05, 0.00), (1.10, 0.00), (1.15, 0.00), (1.20, 0.00), (1.25, 0.00), (1.30, 0.00), (1.35, 0.00), (1.40, 0.00), (1.45, 0.00), (1.50, 0.00), (1.55, 0.00), (1.60, 0.00), (1.65, 0.00), (1.70, 0.00), (1.75, 0.00), (1.80, 0.00), (1.85, 0.00), (1.90, 0.00), (1.95, 0.00), (2.00, 0.00)

CPR = GRAPH(DVS)

(0.00, 0.5), (0.1, 0.5), (0.2, 0.4), (0.3, 0.3), (0.4, 0.17), (0.5, 0.13), (0.6, 0.1), (0.7, 0.07), (0.8, 0.05), (0.9, 0.03), (1, 0.02), (1.10, 0.01), (1.20, 0.00), (1.30, 0.00), (1.40, 0.00), (1.50, 0.00), (1.60, 0.00), (1.70, 0.00), (1.80, 0.00), (1.90, 0.00), (2.00, 0.00)

CPS = CPPS*(1-CPR)

ddist = 0.0025*MaxStemb

DVS = if stemp<TFLOW then STEMP/TFLOW ELSE 1+((STEMP-TFLOW)/(TMAT-TFLOW))

EYS = pEYS*EYSn

EYSn = GRAPH(TIME)

(75.0, 0.00), (150, 0.00), (225, 0.01)

FHB = pFHB*FHBn

FHBn = GRAPH(TIME)

(75.0, 0.01), (225, 0.01)

FST = pFST*FSTn

FSTn = GRAPH(TIME)

(75.0, 0.00), (150, 0.00), (225, 0.01)

grain__yield = 0.85*EarB

k = 0.65

LAI = LeafB*SLA*((1-PM)^BetaPM)*(1-SNB)*((1-STB)^BetaSTB)*((1-YR)^BetaYR)*(1-BR)

multact = 0.001

pAPHN = 0

PartLS = PartL+PartS

pBR = 0

pBYDV = 0

pEYS = 0

pFHB = 0

pFST = 0

PM = pPM*PMn

PMn = GRAPH(TIME)

(75.0, 0.00), (100, 0.001), (125, 0.002), (150, 0.003), (175, 0.0065), (200, 0.01), (225, 0.01)

pPM = 0

pRUE = 1

pSHY = 0

pSNB = 0

pSTB = 0

pTAK = 0

pWEED = 0

pYR = 0

RAD = GRAPH(TIME)

(75.0, 7.80), (105, 13.0), (135, 16.3), (165, 17.5), (195, 15.6), (225, 13.8)

rfaph = max(1-(Honey*0.015),0.8)

rrsap = GRAPH(TIME)

(75.0, 0.45), (90.0, 0.45), (105, 0.45), (120, 0.45), (135, 0.45), (150, 0.45), (165, 0.45), (180, 0.45), (195, 0.32), (210, 0.2), (225, 0.24)

rrsen = GRAPH(DVS)

(0.00, 0.00), (0.2, 0.00), (0.4, 0.00), (0.6, 0.00), (0.8, 0.00), (1.00, 0.00), (1.20, 0.01), (1.40, 0.025), (1.60, 0.04), (1.80, 0.1), (2.00, 0.1)

rsap = rrsap*aphfw

RUE = GRAPH(DVS*pRUE)

(0.1, 1.20), (0.3, 1.20), (0.5, 1.20), (0.7, 1.20), (0.9, 1.20), (1.10, 1.10), (1.30, 1.10), (1.50, 1.10), (1.70, 1.10), (1.90, 1.10), (2.10, 1.10)

sfwaph = GRAPH(TIME)

(75.0, 0.00), (85.7, 0.00), (96.4, 0.00), (107, 0.05), (118, 0.1), (129, 0.15), (139, 0.2), (150, 0.25), (161, 0.316), (171, 0.316), (182, 0.283), (193, 0.25), (204, 0.33), (214, 0.415), (225, 0.415)

SHY = pSHY*SHYn

SHYn = GRAPH(TIME)

(75.0, 0.00), (150, 0.00), (225, 0.01)

SLA = GRAPH(DVS)

(0.00, 0.037), (1.00, 0.018), (2.00, 0.017)

SNB = pSNB*SNBn

SNBn = GRAPH(TIME)

(75.0, 0.00), (100, 0.0003), (125, 0.0006), (150, 0.001), (175, 0.0055), (200, 0.01), (225, 0.01)

STB = pSTB*STBn

STBn = GRAPH(TIME)

(75.0, 0.00), (100, 0.0003), (125, 0.0006), (150, 0.001), (175, 0.0055), (200, 0.01), (225, 0.01)

TAK = pTAK*TAKn

TAKn = GRAPH(TIME)

(75.0, 0.0005), (100, 0.001), (125, 0.0015), (150, 0.002), (175, 0.006), (200, 0.01), (225, 0.01)

TBASE = 0

TFLOW = 1600

TMAT = 2500

TMAX = GRAPH(TIME)

(75.0, 8.90), (105, 12.4), (135, 17.3), (165, 20.5), (195, 21.4), (225, 21.5)

TMIN = GRAPH(TIME)

(75.0, 1.20), (105, 3.30), (135, 7.30), (165, 10.3), (195, 12.2), (225, 12.0)

WEED = pWEED*WEEDn

WEEDn = GRAPH(TIME)

(75.0, 0.00), (100, 2.00), (125, 4.00), (150, 6.00), (175, 8.00), (200, 10.0), (225, 10.0)

YR = pYR*YRn

YRn = GRAPH(TIME)

(75.0, 0.00), (100, 0.0003), (125, 0.0006), (150, 0.002), (175, 0.0058), (200, 0.01), (225, 0.00)