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Summary

This document is addressed to a fairly diverse audience. It consists of two main parts. The first part introduces the principles and the general structure of WHEATPEST. We have limited the number of details and equations included in this part, in order to retain only what we feel is essential to be able to see what this simulation model is about, what it does, and what it cannot do. The second part is divided into two more sections. The first contains the details of the WHEATPEST code, for those who are interested in having a more detailed description of the model; and the second consists of a series of recording forms and tables, which are the types of data required to run the model.

1. INTRODUCTION

1.1. Why are crop losses important?

If the well-being of mankind is to be improved or at least maintained over the coming decades while preserving global resources, the performances of global agroecosystems are expected to improve significantly, and this improvement will have to take place while increased constraints to these performances will occur. The improvement is rendered necessary both by the increase of the world population, together with new, or renewed, demand from societies towards the world's agroecosystems, in terms of, e.g., energy production, carbon sequestration, and ecosystems' services. The constraints imply that not only production is expected to increase on a global scale in order to meet mankind’s needs, but that it will have to do so with reduced energetic, chemical, labour, and water inputs; in other words, both inputs efficacy (the amount of produce relative to the levels of inputs) and inputs efficiency (the first derivative of the function: produce output = f(input)) will have to increase.

Given that context, one must ponder that, on the one hand, pests of agricultural plants (any harmful organism to a cultivated plant, whether a pathogen, a weed, an insect, or a nematode) are responsible for crop losses within a range of 20-40% of global agriculture, while on the other hand, management of these pests strongly relies on environmentally unsustainable methods, particularly pesticides, in many countries of the world, in particular in Europe.

One way to addressing such very broad issues is to classify and rank the importance of individual crop pests. This document introduces a (modelling) approach to address this issue, and develops such a hierarchy in the case of wheat pests in Europe. This approach takes into account the variation in agricultural contexts, which affects the importance of crop pests. Another issue is to consider future (and in many cases, unavoidable), changes that agriculture will experience, and their consequences on the harmfulness of pests. A third type of question concerns the efficiency and the efficacy of current, or future, plant health management tools and strategies. This document introduces a modelling approach to address such questions.

Crop losses, qualitative or quantitative, are also losses in the investment to agroecosystems, whether energy, knowledge, labour, soil, water, or chemical. As a result, the reduction of direct, marketable, agricultural outputs from agricultural systems caused by crop pests also corresponds to attrition of other, diverse, and important services of ecosystems.

This generates a dilemma, since crop losses at such magnitude on a global scale do not correspond to attrition in harvested and marketed produce only, but also therefore translate into commensurate losses in energetic, water, knowledge, economic, and environmental (especially water) resources. Accepting such losses therefore is not sustainable from a societal or an environmental standpoint; simultaneously current methods often used to mitigate the impact of pests of agroecosystems' performances have to be questioned.

1.2. A thinking framework

One step to better develop a reasonable research framework is to analyse the relationships between cultivated, growing crops with their pests; and the effects of these pests on crop performances. These relationships are in essence dynamic. The approach we therefore emphasise here is a simulation modelling one; however, the purpose in this document is to emphasise the modelling framework, rather than the modelling details.

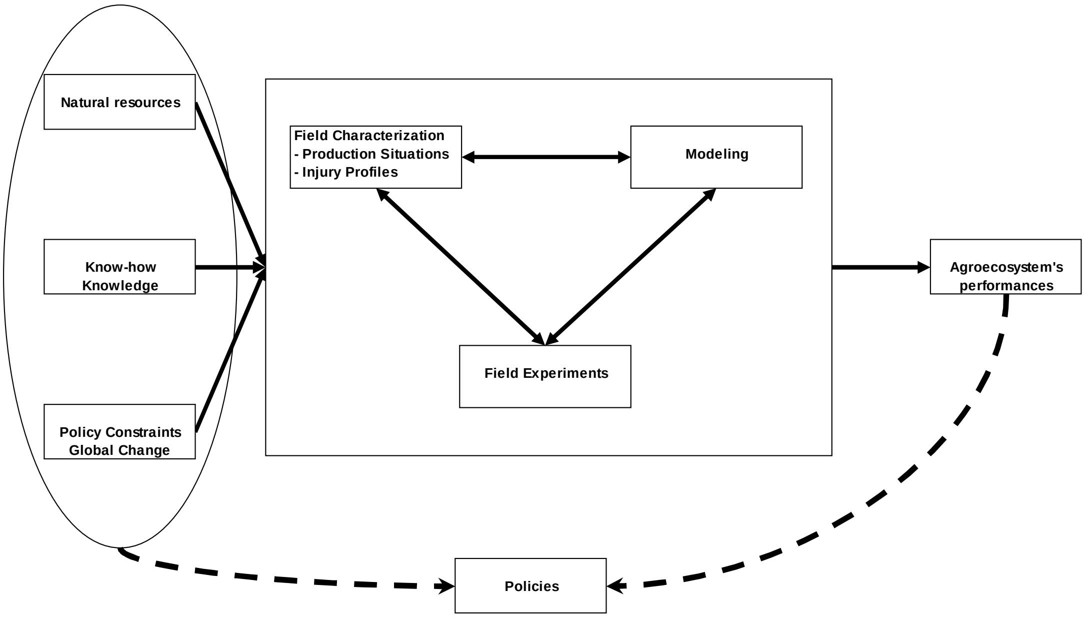

Figure 1. A framework to addressing the effects of crop pests on agroecosystems' performances.

A rough framework for thinking is outlined in Figure 1. The outer layer of the chart includes a first set of components such as 'natural resources', 'know-how and knowledge', and 'constraints to production', which may be seen as inputs to a system. The term 'constraints to production' is a very broad one, and may include components of global or local current change, such as agricultural or environmental policy changes, agricultural water shortage, or reduced energy, or labour, and availability. The outer layer also includes 'agroecosystems' performances', which may be seen as an output of this system. Crop yield is one of these performance characteristics, although it is not, by far, be the only performance a given agroecosystem has. In order to assess the performances of the system, one needs to compare outputs with inputs, and this may lead to policies, including research prioritisation.

The inner part of the diagram has three interacting components: field experiments, characterisation, and modelling. Characterisation, in the context of this document, focuses on two key aspects: production situations and injury profiles. These terms will be introduced later-on in this text; suffice it to say for now that the two aspects are essential to assess, to understand, and to model the impact of a chosen set of crop pests in a given agricultural environments — this is because the impact of crop pests will depend on the agricultural environment, which therefore may be seen as a prior information to processing pest injury information. In this document, we shall speak little (but much refer to) experimental work, which is necessary to derive parameter values, assess model performances, and test hypotheses. Again, no experiment could possibly be designed without a production situation and an injury profile to be referred to, even implicitly. Modelling represents the phrasing, in a programming code, of hypotheses derived from a characterisation work (which generates inferences) and from an experimental work (where deductions may be made); in many ways, a model, as used in this document, may be seen as a medium for linking inferences and deduction. The model which is presented here, however, is aimed at the additional purpose of scenario exploration. The very reason for this is that crop losses caused by pests are not, and cannot, be measured per se, as, for example, a yield or leaf area index can be. Crop losses may be assessed only through careful experimental work in the field, or can be analysed by modelling scenarios where injuries do and do not occur.

The purpose of this working document is to share concepts and views, as much as it is to share and document a simulation model code. After all, many simulation models have been developed in the past 40 years; we believe this simulation model is useful, but only within a set of concepts that would be shared with the reader. A few key concepts are thus briefly summarised below.

1.3. What is a production situation?

This document deals with wheat, in particular with winter wheat (although a few changes in parameter values would render the model code suitable for spring wheat), with pests in winter wheat, and with wheat management in Europe. Research conducted on many different crops in the world is here to show that crop management, obviously, do not occur randomly. Crop management is a reflection of farmers' adaptation to their economic, social, and physical environment. The concept of production situation (PS) encapsulates this notion. It shows us that, in a given environment, at a given geographical scale, a particular production situation will prevail, and even perhaps be the only one that is being encountered. But it also shows us that between two neighbouring farms which are managed by farmers with different connections, different strategies, or differing views on how to maintain the land, the production situation will vary. It even shows us that, within a farm, two fields that are assigned to different roles in a cropping system may correspond to two different production situations; in that case, one step from one field to another would imply a shift in production situation, and a dramatic change in the way the crop looks, grows, develops, and yields. Another concept close to that of a production situation is that of attainable yield. A given production situation corresponds to a certain level of attainable yield. This is to imply that, assuming that no reducing factors occur, the actual, harvested yield of the crop would match that attainable yield level. Reducing factors in agriculture are numerous; these include hail, typhoons, frost, and biological factors. Here, we focus on biological factors, pests.

1.4. Defining crop losses (damage), simple and multiple injuries, and pest guilds.

Figure 2 provides a pictorial definition of a quantitative damage, that is, a yield loss caused by crop pest. The definition refers to two levels of yield, actual and attainable. The attainable yield is what a farmer harvests. It accounts for the effects of limiting factors (which define a given level of attainable yield in a given field, were no reducing factors occurring during the cropping season), as well as the effects of reducing factors, in particular crop pests. Damage is a more modern term to speak of crop losses; the two terms are used interchangeably here.

The damage a farmer could experience with his crop is usually not linked to one single pest during a given cropping season. Rather, what is experienced more often is a number of different pests, occurring possibly at different stages of the crop growth. In most cases, these pests are of no immediate concern, but some are, and in many cropping seasons of a farmers' experience, one has had to worry about several pests in the same season. There are very few simulation models that handle several pests at a time, and even fewer that have a definite objective of doing so in the simplest possible way. WHEATPEST, the simulation model introduced in this document, attempts to do so.

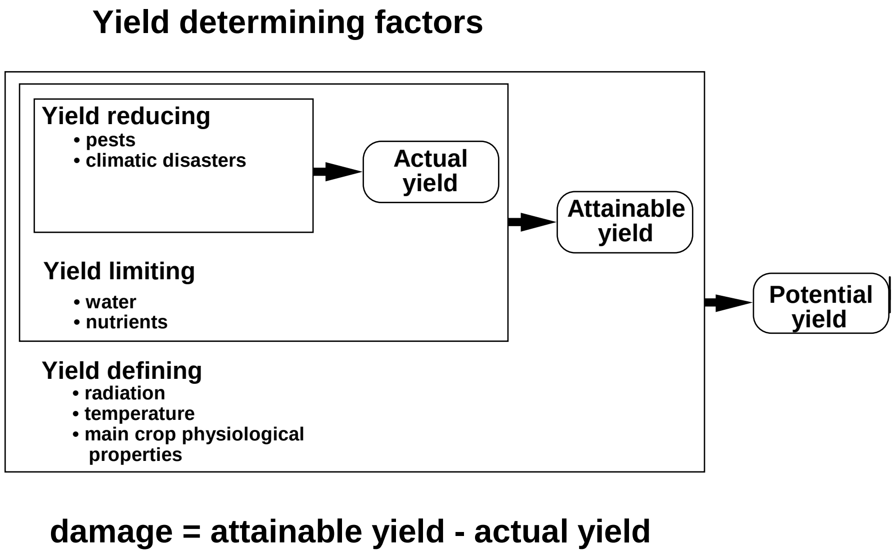

Figure 2. Factors determining potential, attainable, and actual yield, and crop losses (damage).

There is a wide variety of harmful organisms on wheat. They differ in their taxonomic groups, in their life cycles and biology, and in the way they interact with a wheat crop. Community ecology, a growing branch of current ecology, might be tempting and one might contemplate the project of addressing the co-dynamics of this community of wheat pests within its variable and growing host plant population. Surely, such a project has merit. It however would require considering each pest in turn, its biology, its relationships with the physical environment (mediated by the growing crop stand, and affected by management practices), and with numerous, variable, human interventions.

1.5. Recent avenues that make modelling of multiple pest damage possible

Another group of question lies in the harmfulness, individual or collective, of wheat pests. This is a core group of questions: it enables answering questions pertaining to the specific importance (in terms of damage) of each individual pest—assuming the presence of other pests, or pertaining to the overall damage caused by a group of pests. This core group of questions can more readily be answered because of two major avenues that have been developed over the past 20 years. First, pests may be widely diverse in terms of their taxonomic groups, biological cycles, or environmental requirements; however, they do belong to specific guilds in the way they can harm a crop. This implies that a given pest will make use of a few mechanisms through which it will affect host plant growth and development. Second, pests, and the injury they cause in a cultivated crop stand, do not occur at random. Several studies on a number of crops worldwide show that, on the contrary, patterns emerge whereby injuries caused by a given pest tend to be associated with other injuries. Injury profiles therefore tend to develop. Further, such injury profiles have been shown in several instances to be associated with production situations, and in particular with crop management.

These two points bring leverage to developing a comparatively simple approach to understanding a complex system: the same injury mechanisms are shared by several, very different, pests: this facilitates the development of field assessment schemes and scales, and the writing of equations representing injury mechanisms in a modelling program; and injuries tend to group into injury profiles: this implies that one does not have to consider a tremendous number of possible pest combinations; only a few of them are relevant; further, these are relevant in given production situations only; the number of current scenarios to be considered may therefore be restricted to what actually occurs, the current combination of production situations by injury profiles.

The concepts of production situation, injury profile, injury mechanisms, attainable yield, and actual yield are the basis of this document, the modelling approach it proposes, and the modelling framework it outlines. However, in order to efficiently mobilise these concepts in the perspective of prioritisation research and detecting knowledge gaps, another prerequisite is simplicity. The modelling work presented here attempts to retain the essence of processes that are, in many cases, extremely complex (and worth research of their own). This is a risk which is taken gladly, as transparency is key to sharing knowledge, and essential for model evaluation.

2. PART I: RATIONALE AND GENERAL STRUCTURE OF WHEATPEST

2.1. What is WHEATPEST?

WHEATPEST is a simple crop growth model for winter wheat which incorporates damage mechanisms caused by several pests (pathogens, insects, weeds), and which simulates the physiological effects of these pests on crop growth and yield.

2.2. What are the yield levels modelled by WHEATPEST?

The model enables the simulation of three levels of yield (Figure 3):
First, the model can simulate the attainable yield in a given production situation, that is, the yield achieved when no injuries caused by pests occur, in other words, when injuries levels are set to 0.
Second, a range of simulations can be done in the same production situation, that is to say, in contexts where the attainable yield is the same, simultaneously with one or several pests being present. These simulations will generate several levels of actual yield, that is to say, of attainable yield reduced by the harmful effect of one or several pests.
If only one pest is considered, the injury level of this pest is introduced in the model and the injuries levels of the other pests are kept to 0. In this case, the model simulates yield reduced by one pest, i.e. the previous actual yield reduced by the pest introduced. Thus, the relative damage of each pest can be assessed as the difference between the attainable yield (injuries levels set to 0) and the actual (damage-reduced) yield.
Simulations can also be done with several pests, and the simulated yield corresponds to the (attainable) yield reduced by injuries caused by this series of pests. A combination of injuries caused by pests (i.e., the successive levels of injuries for each pest) is called an injury profile. Thus, the model simulates the actual yield which corresponds to a given combination of (i) a production situation, where (ii) an injury profile occurs. Yield loss (damage) is measured as the difference between the simulated attainable yield and the actual yield.

The reader will find in this first part most of the elements one needs to understand how WHEATPEST works, the kind of data the model requires to run, and elements to interpret the outputs of the model. Readers interested into the details of the modelling structure will find additional details in Annexes 1 and 2.

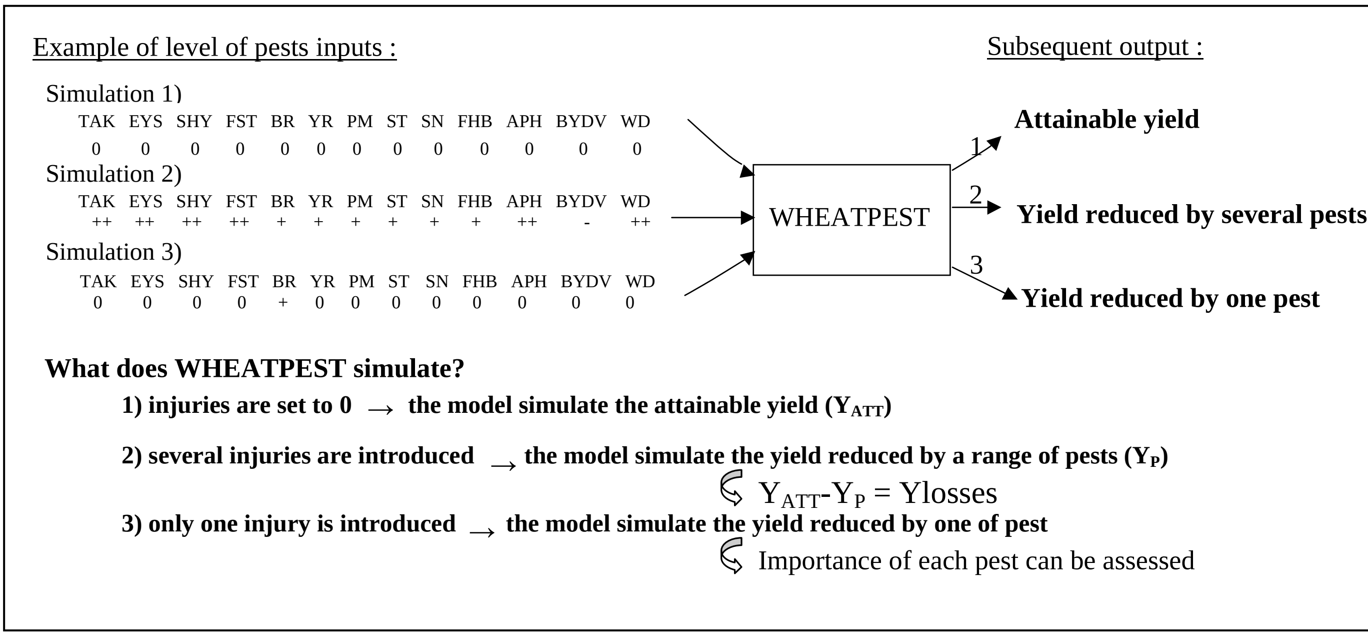

Figure 3. Different types of simulations using WHEATPEST.
TAK: take-all; EYS: Eye-spot; SHY: Sharp eyespot; FST: Fusarium stem rot; BR: Brown rust; YR: Yellow rust; SN: Septoria nodorum; FHB: Fusarium head blight; APH: Aphids; BYDV: Barley yellow dwarf viruses; WD: weeds. For simplification, the different levels of injuries are presented by : 0: none, +: slight level; ++: moderate level; +++: high level

2.3. Presentation of the model structure

The system modelled is a 1 square meter of winter wheat crop, from early spring to crop maturity. The period from sowing till the end of winter is not modelled, and the crop is therefore assumed to have been established prior to this period. In other words, the model runs on the basis of a given crop establishment status, which has to be fed into the model as input information. The time-step of the model is one day, that is to say that changes in the status of the crop are updated, or incremented, on a daily basis, using several daily input variables the model is fed with. WHEATPEST is based on a very simple, generic, crop physiological structure; therefore the daily information that influences changes in state variables consists of a few weather variables only.
The model simulates the dynamics of biomass of wheat crop organs: roots, stems, leaves and ears. Grain yield is computed from ear biomass at crop maturity. The model incorporates the processes required to simulate effects of (1) a given production situation, and (2) pest injuries on crop physiology. The simplified structure of the model is given in Figure 4.

WHEATPEST concentrates on the effects of harmful organisms, that is to say, any organism that may reduce the physiological performances of the system, which we refer later-on to as 'pests', including weeds, pathogens, and insects (these pests are listed in Table 1). The overall structure of the model was designed to account for these effects. The successive levels of injuries caused by pests to the wheat crop represent a second group of variables, in addition to weather variables, that influence the behaviour of the system. This second group is addressed later-on in this document.

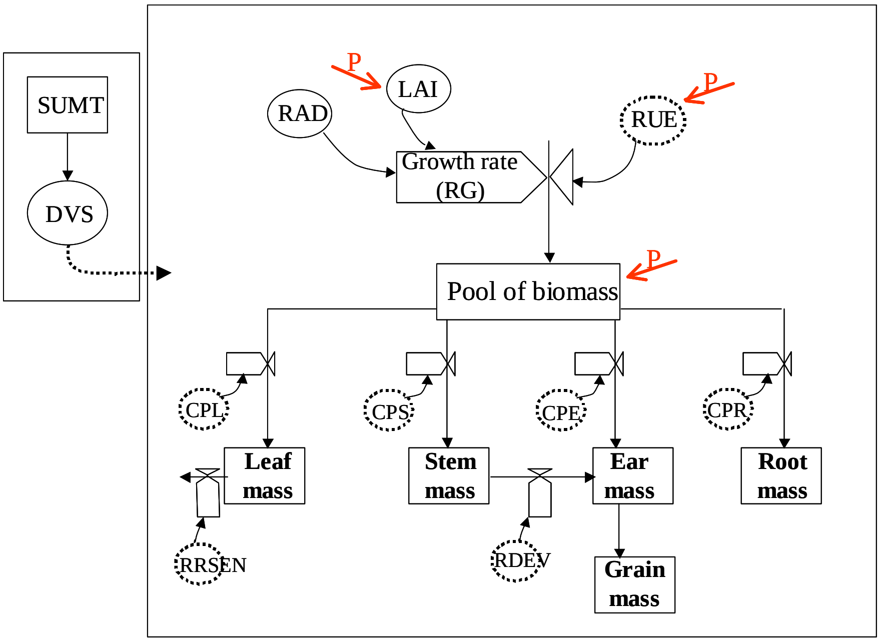

Figure 4. Schematic representation of the wheat growth and yield model.
parameter depending on DVS.
P: damage mechanisms
CPE: coefficient of partitioning in ears; CPL: partitioning coefficient to the leaves; CPS: partitioning coefficient to the stems; CPR: partitioning coefficient to the roots; DVS: crop development stage; LAI: leaf area index; RAD: daily radiation; RDEV: rate of development; RRSEN: relative rate of leaf senescence; RUE: radiation use efficiency; SUMT: sum of temperature.

Disease	Name (teleomorph)	Name (anamorph)
Aphids	*Sitobion avenae*	
Barley Yellow Dwarf Viruses		
Brown rust (Leaf rust)	*Puccinia triticina*	
Eyespot (Foot rot, Strawbreaker)	*Oculimacula yallundae* *O. acuformis*	*Pseudocercosporella herpotrichoides*
Fusarium Head Blight Fusarium Stem Rot	*Gibberella zeae* *G. avenacea* *F. culmorum* *Microdochium nivale*	*Fusarium graminearum* *F. avenaceum*
Powdery Mildew	*Blumeria graminis*	*Oidium monilioides*
Septoria tritici blotch	*Mycosphaerella graminicola*	*Septoria tritici*
Septoria nodorum blotch	*Leptosphaeria nodorum*	*Septoria nodorum*
Sharp-eyespot	*Ceratobasidium cereale*	*Rhizoctonia cerealis*
Take-all	*Gaeumannomyces graminis var. tritici*	
Weeds		
Yellow rust (Stripe rust)	*Puccinia striiformis*	*Uredo glumarum*

Table 1. Pests considered in WHEATPEST. Please note that this list is not complete, some of its items removed, and others not listed here, added.

2.3.1. Modelling growth and attainable yield

Most of the processes that determine the dynamics of crop growth are driven by crop development, represented by its successive phenological stages. In cereals, one may distinguish two major phases: vegetative and reproductive. Following several other simplified crop growth models, three key development stages (DVS) are used in WHEATPEST: 0, 1, and 2, which correspond to crop establishment, flowering, and crop maturity, respectively. WHEATPEST therefore considers only essential phases in the physiology of the crop. This is what DVS = 0, or 1, or 2 means. Crop development stages are computed as a function of thermal time from crop establishment (with a temperature base of 0℃).

The rate of growth (RG) of daily increase in biomass (expressed in $g.m^{-2}.day^{-1}$) is modelled on the basis of Monteith's equation (Monteith, 1977):

$$RG = RAD \times RUE \times \left[1 - \exp^{(-k \times LAI)}\right]$$

Where RAD is the daily radiation ($MJ.m^{-2}.day^{-1}$), RUE is the radiation use efficiency ($g.MJ^{-1}$), k is the light extinction parameter (-), and LAI is the leaf area index ($m^2.m^{-2}$).

This equation may be seen as the ‘core’, or the ‘engine’ of the model. It has been used in many models. In particular, the efficiency with which a crop canopy converts intercepted light energy into plant biomass, or radiation use efficiency, RUE, which depends on the crop development stage, is a key parameter. Of course, RUE also depends on a number of other factors. WHEATPEST distinguishes two groups of such factors. One is the range of factors that influence the physiological efficiency of energy conversion and transfer, which is referred to later-on by the production situation. Another group, which is the prime reason for using this model, is the series of injuries that pests may cause during the crop cycle history of a wheat stand; we refer to this second group as the injury profile.

After radiation (RAD) interception ([1-exp(-k LAI)]) and conversion (RUE) into assimilates, these are then partitioned towards the different organs. The fraction of partitioning depends on the development stage. For example, partitioning towards roots is very early in the crop development stage, but tapers off and becomes negligible even before the reproductive stage is reached; on the contrary, partitioning to the ears starts at flowering, and is near-exclusively directed towards ears soon afterwards.

Starting flowering, two processes are modelled. The first one is leaf senescence. The second one is the transfer of carbohydrates that had been stored during the vegetative phase from stems to ears.

Leaf senescence depends on DVS and its rate is a function of the production situation. It is introduced in the model as a reduction of the photosynthetic leaf area (LAI) and consequently as a reduction of the rate of growth (RG).

The redistribution of the reserves accumulated in the stems is a function of the stem biomass at flowering (20% are considered to be redistributed); the rate of redistribution is also a function of the production situation.

The minimum set of data required for modelling growth and attainable yield of a wheat crop stands, i.e. data inputs, is reported in Table 2. For more details, the reader interested in the collection of these data can refer to PART2 and Annex 3 where some examples of calculations and procedures for data collection are shown.

Daily weather data
- minimal and maximal temperature (TMIN, TMAX) - global solar radiation (RAD)
Parameter depending on variety type
- coefficient of light extinction (k)
Parameters whose values depend on the production situation (PS) and evolve with DVS. These parameters are also considered as driving functions .
- development stage function of the sum of temperature; [DVS=f(SUMT)] - radiation use efficiency; [RUE=f(DVS)] - coefficients of biomass partition to the roots, stems, leaves and ears; [CPR, CPS, CPL, CPE=f(DVS)] - specific leaf area used to compute the LAI; [SLA=f(DVS)] - relative rate of leaf senescence; [RRSENL=f(DVS)] - rate of development used to compute the rate of redistribution of the reserves from the stems to the ears; [RDEV=f(DVS)]

Table 2. Minimum set of data required for modelling attainable growth and yield using WHEATPEST.

2.3.2. Damage mechanisms

In its current version, WHEATPEST considers 13 pests. These organisms that are harmful to wheat were included because they are known to cause important damage to the crop, and/or because the data required to model their effects on a wheat crop stand are available. Not all major wheat pests have yet been considered in the model, however. Of course, when new needs arise (important pests that have not yet been included, or new pests that need to be considered), additional pests may be included into the model. This is possible because the structure of the model is generic, and because the ways pests are seen in their effects on wheat are classified in categories.

Crop pests can be classified as
- pests that cause injuries on roots, such as: (1) Take-all; (2) Fusarium stem rot
- pests that cause injuries on stems, such as: (3) Eyespot; (4) Sharp eyespot, Fusarium stem rot;
- pests that cause injuries on leaves, such as: (5) Brown rust, (6) Yellow rust, (7) Powdery mildew, (8) Septoria tritici, (9) Septoria nodorum, (10) Aphids;
- pests that cause injuries on ears, such as (11) Fusarium head blight;
- and pests that affect the overall yield performance of a wheat stand, such as: (12) Barley yellow dwarf viruses; (13) Weeds and aphids.

Further, these pests can be described according to the **damage mechanisms** they cause. For example, damage mechanisms can be:
- a reduction of the light intercepted by the leaves due to foliar pests which cause lesions and consequently a reduction of the photosynthetic area. These pests can be described as 'light stealers'.
- a decrease in the photosynthetic rate (efficiency) due to reductions in nutrient and water uptake following a disturbance in the phloem vessels (BYDV, Take-all, Eyespot, Sharp eyespot and Fusarium stem rot), or following competition (weeds) or honeydew deposition (aphids).
- a diversion of assimilates by lesions for the production of propagules or by suking insects such as aphids.
- a direct or indirect impact on grain biomass induced by grains colonisation (FHB) or lodging effect (Eyespot).

These damage mechanisms are incorporated in the model as reductions of LAI (e.g., presence of lesions on leaves), reduction of RUE (e.g., presence of lesions on stems hampering nutrients transportation), and in assimilate diversion (e.g., phloem sapping by aphids) (Fig.4).

We provide here two examples showing how damage mechanisms are included in WHEATPEST (please note the underlying simplifying hypotheses). Annex 1 provides details on the other injuries.

Example 1: Take-all

Take-all affects RUE proportionally to root take-all disease severity (TAK, with 0 ≤ TAK ≤ 100).

$$RG = RAD \times RUE \times \left[1 - \exp^{(-k \times LAI)}\right]$$

$$RG_{TAK} = RAD \times RUE \times RF_{TAK} \times \left[1 - \exp^{(-k \times LAI)}\right]$$

With: $RF_{TAK} = 1 - \frac{TAK}{100}$

In this example, four levels of Take-all severity are considered in the model (TAK0 = 0%; TAK1 = 1%; TAK5 = 5% and TAK25 = 25%). Figure 5 shows the model predictions of these Take-all effects on RUE, RG and the ear dry biomass. At maturity (DVS=2), the ear biomass is reduced by 0.7%, 3.4%, and 16.8% with TAK1, TAK5 and TAK25, respectively.

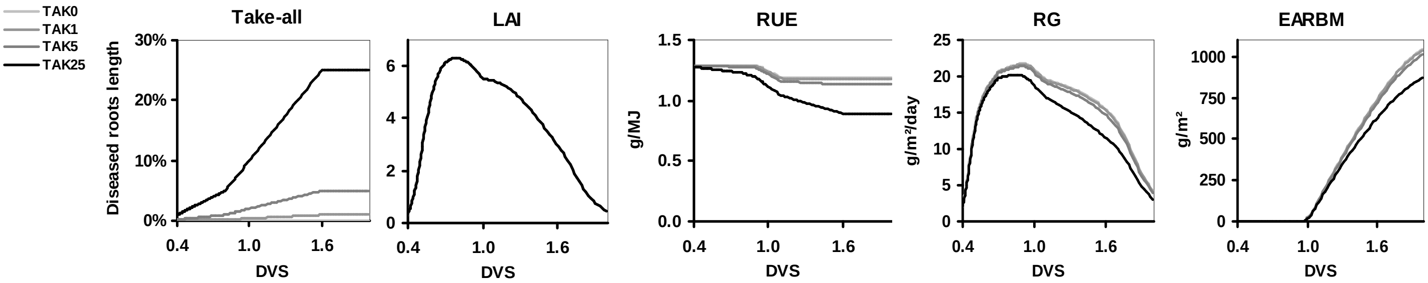

Figure 5. Model outputs of Take-all effect with varying terminal disease severity of 0% (TAK0), 1% (TAK1), 5% (TAK5) and 25% (TAK25).
The four disease progress scenarios (TAK0, TAK1, TAK5, TAK25) are shown in the first box. DVS = development stage (0=sowing, 1=flowering and 2= maturity); LAI = leaf area index; RUE = radiation use efficiency; RG = rate of growth; EARBM = dry biomass of ears.

Example 2: Brown rust

Brown rust injures wheat crop through two mechanisms: a reduction in LAI, and a diversion of assimilates towards lesions for spore production. The LAI reduction is described as:

$$LAI_{BR} = LAI \times \left(1 - \frac{BR}{100}\right)$$

with BR: Brown rust severity (0-100), and the assimilate diversion is described as:

$$RG_{BR} = RAD \times RUE \times \left[1 - \exp^{(-k \times LAI)}\right] - RDIV_{BR}$$

where $RDIV_{BR}$ is the daily rate of assimilate diverted to lesions for spore production. $RDIV_{BR}$ is proportional to the Brown rust severity (BR) (see Annex 1 for more details).

For this example, four levels of terminal Brown rust severity were introduced in the model (BR0 = 0%; BR1 = 1%; BR5 = 5% and BR25 = 25%). Figure 6 shows the model simulation of these Brown rust effects on LAI, RG and the ear dry biomass. At maturity (DVS=2), the ear biomass is reduced by 0.7%, 3.6%, and 16.8%with BR1, BR5 and BR25, respectively.

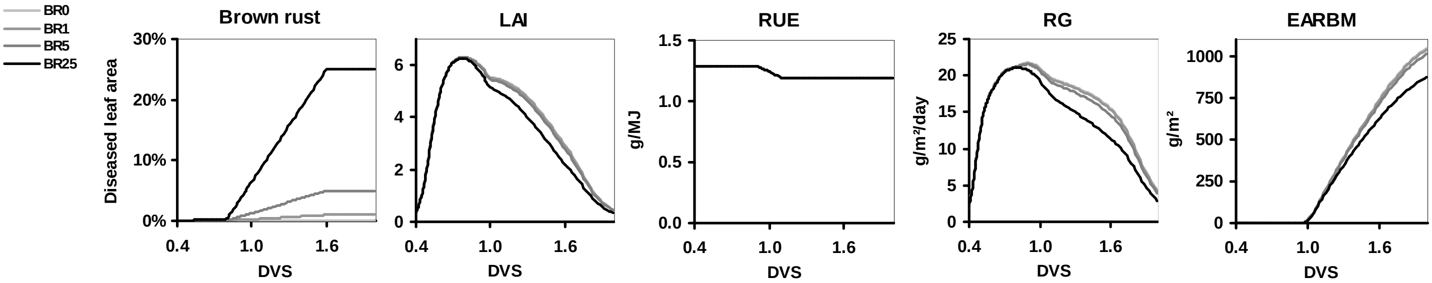

Figure 6. Model outputs of brown rust effect with varying terminal disease severities of 0% (BR0), 1% (BR1), 5% (BR5) and 25% (BR25).
DVS = development stage (0=sowing, 1=flowering and 2= maturity); LAI = leaf area index; RUE = radiation use efficiency; RG = rate of growth; EARBM = dry biomass of ears.

2.4. Working examples

We discuss here three hypothetical scenarios, each of them corresponding to a particular combination of a production situation (PS) with an injury profile (IP), in order to illustrate the approach, the steps taken, and the results and conclusions that can be obtained with the model.

2.4.1. Framework of PS*IP combinations and example of scenarios

In this set of working examples, we use a data set from a hypothetical farmers' field survey and the relationship between data for Production Situation (PS) (including attainable yield) and Injury Profile (IP) is analysed following the occurrence of the different PS*IP combination (Tab.3). Table 3 indicates that some IP are more frequently encountered in particular PSs (e.g.: IP1 occurs more frequently in PS1; or, IP2 is more frequent in PS2). A chi-square test on this type of data would reject the hypothesis of independent distributions of IPs and PSs, and thus suggest that IPs and PSs (or at least some of the PSs and some of the IPs) are associated.

	PS1	PS2	PS3
IP1	N	n	ε
IP2	-	N	n
IP3	ε	-	N
IP4	n	N	n

Table 3. Hypothetical survey: correspondence analyses between production Situation (PS) and Injury profile (IP). Number of occurrence: N = large; n = small number; ε = very small number; - = never observed

A PS is characterised by a series of attributes of the production environment, and is also linked to an attainable yield level. In this simplified example, three PSs are for instance defined according to nitrogen input, water management, pesticides use, tillage practices, crop sequence and variety type) (Table 4).

The corresponding injury profile includes a set of injuries that can quantitatively be measured (e.g., disease severities: % leaf surface affected; incidence: % affected plants, see more details in Annex 1).

For simplification only, the (production situation * injury profiles) associations, PS1*IP1, PS2*IP2 and PS3*IP3 are described in Table 4, and a simplified, categorised, description of these PS*IP combinations is given using three levels of water management, of inputs, and of pests injury.

Table 4. Exemple of 3 Production Situation and 3 Injury Profile associated
N: nitrogen supply; W: water supply; YA: attainable yield
NL: not limiting, HYV: high yielding variety
TAK: take-all; EYS: Eyespot; SHY: Sharp eyespot; FST: Fusarium stem rot; BR: Brown rust; YR: Yellow rust;

	Production Situation (PS)							Injury Profiles (IP)												
Scenario	N	W	Tillage practices	Crop sequence	Pesticides & Herbicides	Variety type	YA (g.m²)	TAK (Roots)	EYS (Stems)	SHY (Stems)	FST (Stems)	BR (Leaves)	YR (Leaves)	PM (Leaves)	ST (Leaves)	SN (Leaves)	FHB (ears)	APH	BYDV	WD
PS1*IP1	+++	NL	-	-	++	HYV	900	++	++	++	++	+	+	+	+	+	+	+	-	++
PS2*IP2	++	NL	+++	++	-	hardy	500	-	-	-	-	++	-	-	-	-	+	++	-	+++
PS3*IP3	++	NL	+	++	+	hardy	700	+	+	+	+	+	++	++	++	++	+	+	-	+

PM: Powdery Mildew; ST: Septoria tritici; SN: Septoria nodorum; FHB: Fusarium head blight; APH: Aphids; BYDV: Barley yellow dwarf viruses; WD: weeds.
-: none, +: slight level; ++: moderate level; +++: high level

In these three examples:
- PS1 corresponds to a hypothetic production situation where productivity is high (YA = 900g/m²).The corresponding IP has a moderate level of roots and stems diseases, low leaf and ear disease injuries (pesticide use), and a moderate level of weed infestation due to simplified tillage practices partly counterbalanced by herbicide applications.
- PS2 corresponds to a production situation where productivity is low (YA = 500g/m²). The corresponding hypothetic IP has a moderate levels of roots and stems diseases (thorough tillage and diversified crop sequence; resistant varieties). Foliar disease injury and weed infestation are high (no fungicide or herbicide use).
- PS3 is associated to a intermediate attainable yield level (YA = 700g/m²). Injuries due to leaf diseases are fairly high, while stem and root disease injuries are assumed fairly low.

2.4.2. Idealised curves for the drivers of Injury Profile.

Simulations were done for each of the three PS*IP combinations. For each simulation, the different levels of injuries corresponding to the idealised injury profiles were fed as input to the model as an injury driver. An injury driver includes a sequence of injury levels that mimic the typical dynamics of injuries occurring during a cropping season. The graphs in Figure 7 show the different pest injury dynamics for the three IP.

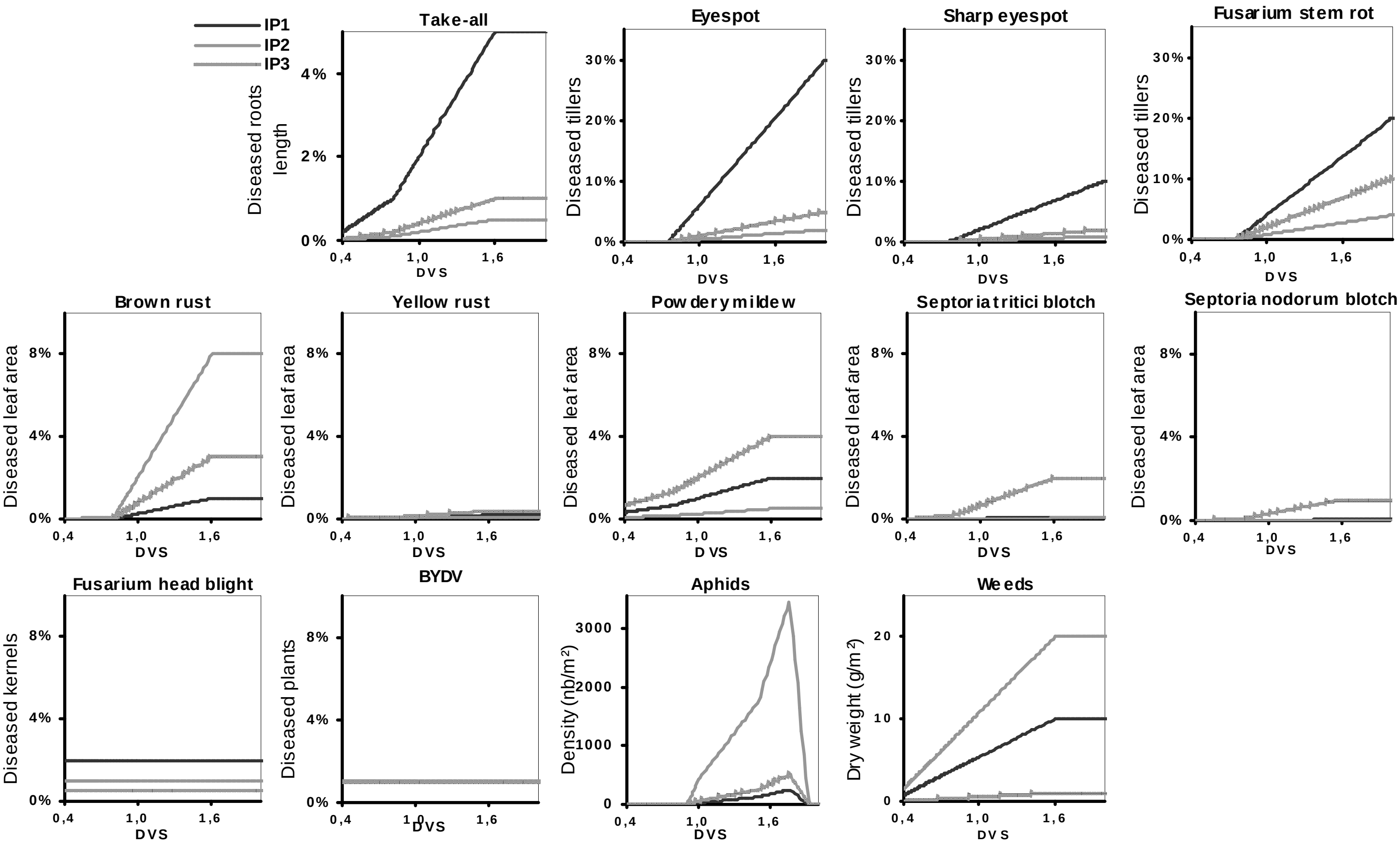

Figure 7. Drivers for Injury Profile.
DVS = development stage (0=sowing, 1=flowering and 2= maturity)

2.4.3. Simulation results

Crop drivers were set to simulate attainable grain yield of 900, 700 and 500 g.m^{-2} for the three production situations (PS1, 2, and 3). The simulations of attainable or reduced growth and yield are shown in Figure 8.

2.4.3.1. Simulation results for attainable growth and yield

The different plant organ biomasses vary similarly in the three production situations (PS1, PS2, PS3), with a maximal dry biomass for PS1, medium for PS2 and minimum for PS3 according to the expected final biomass of grain. The dry biomass of leaves increases in a sigmoid shape until development stage around flowering (DVS=1), then remains stable before decreasing due to physiological leaf senescence. Stems dry biomass increases regularly until flowering and then declines linearly due to carbohydrate re-mobilization to the ears. The dry biomass of roots increases regularly until DVS=0.8, then tapers off and remains stable. Ear dry biomass starts to increase at flowering, and increases nearly linearly until maturity (DV2=2). At this stage, ear dry biomass reaches a final value of 1055, 829 and 590 g.m^{-2} respectively for PS1, PS2 and PS3. The accumulated dry biomass increases regularly according to a concave curve and final total dry biomass are 1861, 1491 and 1107 g.m^{-2} respectively for PS1, PS2 and PS3.
LAI increase regularly until DVS=0.7, and then declines until maturity. Maximum LAI are 6.3, 5.0 and 3.7 m.m^{-2} for PS1, PS2 and PS3 respectively.

2.4.3.2. Simulation results for injury-reduced growth and yield (i.e., actual performances)

The simulations of dry biomass affected by pest injuries are combined to the simulation of attainable growth and yield in Fig.8.
The most important reductions of biomass are obtained on LAI and ears (Table 5). The most important reduction of ear biomass is obtained in the combinations PS1*IP1 and PS2*IP2 (15%); whereas the most important reduction of LAI is obtained in the combination PS3*IP3 (18%).

In Figure 8, relative yield losses are also expressed as percentages of attainable yield for each individual pest. Maximal yield losses of 15.5 and 15% are simulated for the combinations PS1*IP1 and PS2*IP2, respectively. A reduction of 12.5% is observed in the combination PS3*IP3.
In all cases, relative yield losses caused by an injury profile are lower than the accumulated yield losses caused by individual injuries contributing to this profile. Relative yield losses caused by individual injuries are always below 6 % and are below 1 % in more than 50 % of the cases.
In the combination PS1*IP1, injuries on roots and stems (Take-all, Eyespot, and Fusarium stem rot) are responsible for largest fraction of yield losses. These injuries individually cause high relative yield losses, between 2.6 and 3.4 %. Fusarium head blight is individually responsible for 2.2% and weeds account for 2.3% relative yield losses.

In the combination PS2*IP2, Brown rust represent the most important reducing factors for production (individual relative yield losses of 6%) followed by weeds and aphids (with respectively individual yield losses of 4.6 and 2.2 %).
In the system PS3*IP3, yield losses are lower than in the other PSs and are mainly induced by leaf injuries (Powdery mildew, Brown rust and Septoria tritici, which cause respectively 3.8, 2.5 and 1.5% individual relative yield losses) and by Fusarium stem rot which individually cause 1.4% of relative yield losses.
Other injuries cause relative yield losses lower than 1%.

2.4.4. Possible applications of simulation modelling of crop losses in wheat

Several applications of the model may be considered.

First, the model can be used at the field scale to estimate the damage (yield losses) caused by a range of pests or by only one pest. The yield-reducing effect of each pest taken individually can be used to determine a hierarchy of importance of pests for a given combination (useful for strategic research, policy) (see examples of Figure 8).

Second, this model may be used to provide a baseline to structure and guide large scale data collection, i.e., to drive surveys on wheat health and management in Europe. In other words, WHEATPEST could help designing a framework to develop standardised protocols for data collection. One possible objective is to gather a sizeable amount of data on the agricultural conditions in Europe (and so capture the diversity of European wheat field) which will be used to identify the main association of production situations and injury profiles. This should allow building a map of a range yield losses in Europe in interaction with their associated production situation and injury profile.

Third, this model could be used as a tool to analyse simulated outputs under specified scenarios of pest management. The analysis of the SP*IP relationship may also be used to adapt agricultural practices (among with the pest component). Thus, it could be used as a component to guide research priorities for wheat pest management in Europe.

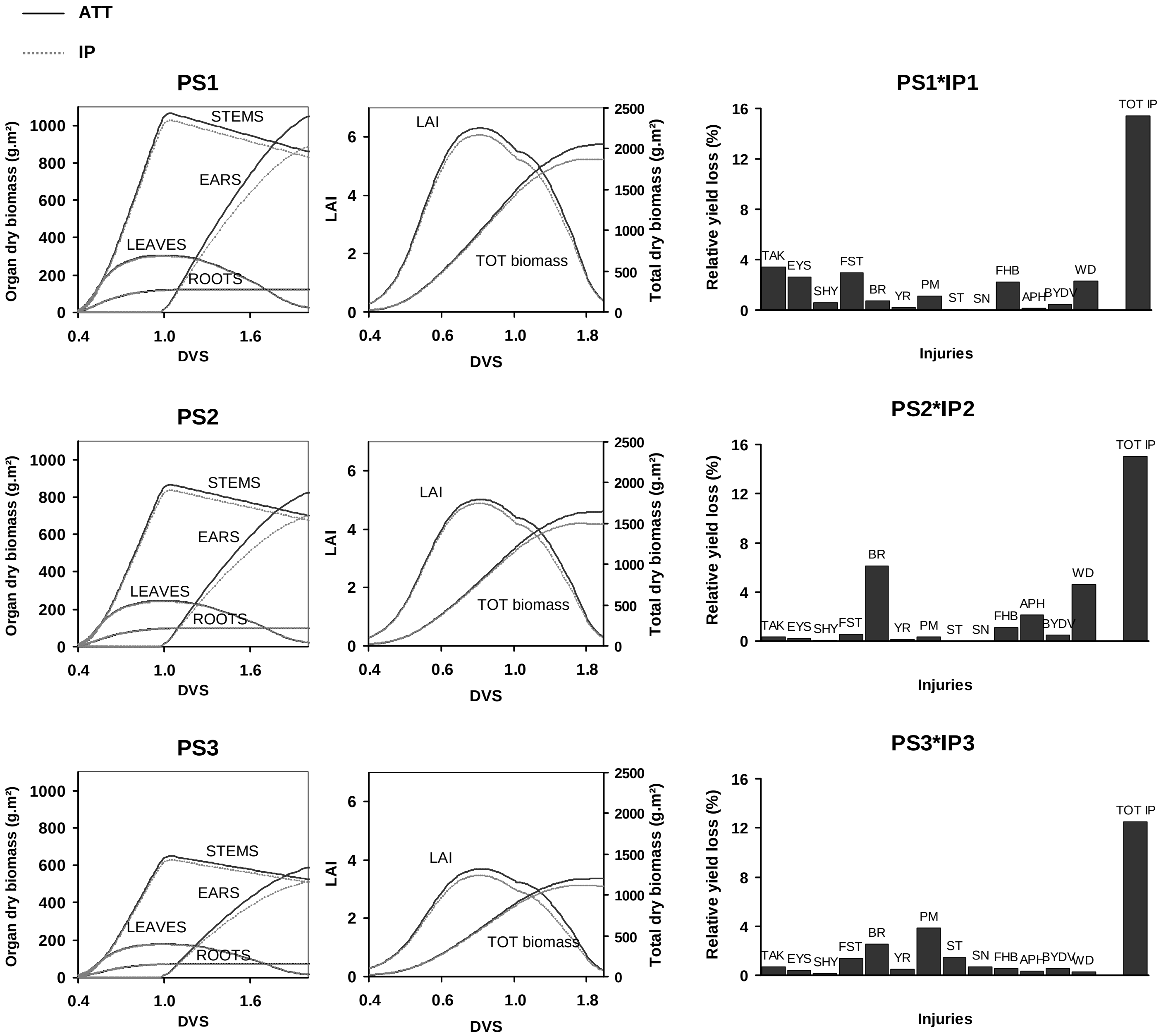

Figure 8. Simulation outputs for three production situations, PS1, PS2, PS3, combined with three injury profiles, IP1, IP2, IP3 (right panel). The panels on the left and centre indicate the time-course of attainable growth (ATT) and of actual (injured) growth (IP). The right panel shows the yield-reducing effect of injury profiles, overall (TOT IP), and for each of their components (successive solid bars). Note that damage is less than additive.

	Leaf	Root	Stem	Ear	Total biomass	LAI	Grain yield
PS1*IP1	2,47 %	2,79 %	3,62 %	15,44 %	9,61 %	8,63 %	15,44 %
PS2*IP2	2,39 %	2,77 %	3,72 %	15,06 %	9,36 %	11,5 %	15,06 %
PS3*IP3	2,89 %	2,95 %	3,43 %	12,48 %	7,83 %	18,32 %	12,48 %

Table 5. Maximum relative yield losses (damage) caused by pests as percent of attainable yield.

The modelling of actual yield, and thus the calculation of yield losses, on the basis of a set of production situations would require functional relationships between production situations and injury profiles. As of today, the available, published, field information is too scarce to include such relationships in a model such as WHEATPEST. Field surveys therefore would be necessary to achieve this objective.

3. PART II: HOW TO USE WHEATPEST?

The reader interested in the use WHEATPEST will find in this second part most of the information needed to 1) understand the code of the model; 2) determine the input data (which we often refer to here as the driving functions of the model) which are required to run the model and the dimensions of these data; 3) compute these driving functions from data measured in the field and 4) measure these data in a field. A protocol for the collection of these data is also given in this section.

The data acquisition protocol corresponds to a series of two types of recording forms. The first one can be used to collect data needed to run the model. The second one is aimed to collect additional information which allow to contribute to surveys for the characterization of the main SP*IP in Europe.

3.1. WHEATPEST code and data input

3.1.1. Code description (see Annex 3)

The code of the model is written in FST (Fortan Simulation Translator; Rappoldt & van Kraalingen 1996). The variables and parameters used are given in Annex 2, and an example of the code is presented in Annex 3. In this example, we present the data used for the PS1*IP1 simulation presented in Part 1.

3.1.2. Data requirements

The model runs on the basis of a given crop establishment status, which has to be fed into the model as an input. In other words, the model requires initial dry biomass of plants: leaves (LEAFBM0), stems (STEMBM0) and roots (ROOTBM0), which are incremented after winter dormancy, i.e. at the start of spring growth (see Annex 2, part B). The Julian day corresponding to the assessment of the initial dry biomass of plants determines the beginning of the simulation (STTIME). The simulation ends at crop maturity (FINTIME).

The model is also fed with climatic variables: minimum and maximum temperatures (Tmin, Tmax respectively) and global radiation (RAD) (see Annex 2, part A). These daily data are inputs used by the model from the beginning till the end of the simulation of a cropping season.

Tmin and Tmax are also required from seedling emergence onwards in order to estimate the initial sum of temperature at the beginning of the simulation (SUMT0).

Simulations also require driving functions pertaining to 1) crop growth (i.e., functions which drive the attainable crop growth for a specific Production Situation, e.g. RUE) and 2) the Injury Profile which a given crop stand is exposed to (i.e., driving functions which provide the dynamics of injuries over crop development).

These driving functions are presented in Annex 2 (part E and F), and some examples of parameterisation are indicated in the following sections.

3.1.2.1. Examples of parameterisation of the driving functions for attainable wheat growth

- Crop development (measured by its stage, DVS) depends on the temperature sum above a temperature threshold (SUMT, C.day). DVS0, DVS1 and DVS2 correspond to seedling emergence, flowering, and maturity, respectively. The actual values of the sum of temperatures at flowering and maturity are required to build the driving function [DVS=function(SUMT)].

- The driving function for the rate of development [RDEV = function (DVS)] is built from the temperature sum above the temperature threshold (SUMT) between the different development stage DVS0, DVS1, and DVS2. For example, the rate of development between flowering and maturity (RDEV2) is computed as follows:

$$RDEV2 = \frac{1}{SUMT_{DVS2} - SUMT_{DVS1}}$$

The quantitative determination of the following driving functions require to collect data at successive sampling dates over crop growth. The data correspond to a 1 m² of crop.
The date (Julian day) of each sampling is used to compute the corresponding development stage. For example, if the leaf biomass (LEAFBM) is assessed at Julian day 80, the sum of temperature (SUMT) since the date of seedling emergence to day 80 is computed and the corresponding development stage is computed with the driving function DVS=function (SUMT).

- The driving function for Specific Leaf Area [SLA = function(DVS)] is derived from assessments of the leaf area index of living leaves (LAI, leaves with at last 50% green area), and the dry biomass of living leaves (LEAFBM). For example, for DVS1:

$$SLA_{DVS1} = \frac{LAI_{DVS1}}{LEAFBM_{DVS1}}$$

- Before flowering (that is, when DVS<1), calculations are necessary to determine the driving functions for partitioning coefficients, with the general form: CP = function(DVS). Four coefficients of partitioning are to be considered: to roots (CPR) (partitioning relative to the total dry biomass); to stems (CPS); to leaves (CPL); and to ears (CPE) (partitioning relative to dry biomass of shoot). These are computed as follows (choosing for example DVS = 0.75):

$$CPR_{DVS0.75} = \frac{(ROOTBM_{DVS1} - ROOTBM_{DVS0.5})}{(PLANTBM_{DVS1} - PLANTBM_{DVS0.5})}$$

$$CPL_{DVS0.75} = \frac{(LEAFBM_{DVS1} - LEAFBM_{DVS0.5}) + (SENLBM_{DVS1} - SENLBM_{DVS0.5})}{(PLANTBM_{DVS1} - ROOTBM_{DVS1}) - (PLANTBM_{DVS0.5} - ROOTBM_{DVS0.5})}$$

$$CPS_{DVS0.75} = \frac{(STEMBM_{DVS1} - STEMBM_{DVS0.5})}{(PLANTBM_{DVS1} - ROOTBM_{DVS1}) - (PLANTBM_{DVS0.5} - ROOTBM_{DVS0.5})}$$

$$CPE_{DVS0.75} = 1 - (CPS + CPL)_{DVS0.75}$$

Where:
ROOTBM = dry biomass of roots
PLANTBM = total dry biomass of plants
LEAFBM = dry biomass of living leaves (leaf with at last 50% green area)
SENLBM = dry biomass of senescent leaves (leaf with less than 50% green area)
STEMBM = dry biomass of stems

After flowering (DVS≥1), the coefficients of partitioning to stems (CPS) and leaves (CPL) are set to 0, while the coefficient of partitioning to ears (CPE) is set to 1.

- The driving function for the relative rate of leaf senescence [RRSENL = function(DVS)] is calculated as follows:

Before flowering (DVS<1) (for example at DVS = 0.75):

$$RRSENL_{DVS0.75} = \frac{SENLBM_{DVS1} - SENLBM_{DVS0.5}}{LEAFBM_{DVS0.5}} / (DOY_{DVS1} - DOY_{DVS0.5})$$

After flowering (that is, when DVS≥1), leaves development is completed. Thus, the relative rate of leaf senescence (RRSENL), can be computed as (for example at DVS = 1.5):

$$RRSENL_{DVS1.5} = \frac{LEAFBM_{DVS1} - LEAFBM_{DVS2}}{LEAFBM_{DVS1}} / (DOY_{DVS2} - DOY_{DVS1})$$

Where:
DOY = Julian day
SENLBM = dry biomass of senescent leaves (leaf with less than 50% green area)

LEAFBM = dry biomass of green leaves (leaf with at last 50% green area)

- The radiation use efficiency driving function [RUE = function(DVS)] is derived as (for example at DVS = 1):

$$RUE_{DVS1} = \frac{(PLANTBM_{DVS0.5} - PLANTBM_{DVS1.5})}{\left(\sum_{DVS0.5}^{DVS1.5} RAD \times (1 - \exp^{-k \times \frac{LAI_{DVS0.5} + LAI_{DVS1.5}}{2}}\right)}$$

Where:
PLANTBM = total dry biomass of plants

$\sum_{DVS0.5}^{DVS1.5}$ RAD = sum of the daily global radiation between DVS0.5 and DVS1.5

LAI = leaf area index of living leaves (leaf with at last 50% green area)

RUE need to be computed only on healthy plants (i.e., without pest).

3.1.2.2. Examples of parameterisation of driving functions for injuries.

Constructing the driving functions for injuries requires assessments of injuries over a growing season. As for the crop growth driving functions, these driving functions are scaled on the development stage of the crop. The date (Julian day) for each injury assessment is therefore used to compute the corresponding development stage.

- The assessment of the number of aphids per square meter of wheat crop (APH) is used to built the driving function [APH = function (DVS)].

For simplification, the values of Rossing (1991) can be used for the relative feeding rate (RRSAP) driving function and the values from Mantel et al., (1982) can be used for the driving function of an individual aphid fresh weight (APHBM). (values in Annex 3).

- The driving function [WD = function(DVS)], is computed from the total dry biomass of weeds per square meter (WD) which is assessed at different dates.

- The Barley Yellow Dwarf Viruses driving function [BYDV = function(DVS)] is built from assessments at different dates of the percentage of plants which present symptoms of BYDV. For example:

$$BYDV_{DVS1} = \left(\frac{PLANTNB_{BYDV}}{PLANTNB}\right)_{DVS1}$$

$PLANTNB_{BYDV}$ = number plants with symptoms of BYDV
PLANTNB = number of observed plants

- The driving function [TAK = function(DVS)], is computed from assessments of the root disease severity due to Take-all (TAK) at different dates. TAK can be visually assessed by the percentage of diseased root system.

- The driving functions for Eyespot [$EYS_{(1,2,3)}$ = function(DVS)] and Sharp Eyespot [$SHY_{(1,2,3)}$ = function(DVS)], are built from assessments at different dates of the percentage of tillers with slight (EYS1, SHY1), moderate (EYS2, SHY2) and severe (EYS3, SHY3) Eyespot or Sharp Eyespot symptoms.

These different levels of symptoms are described by Scott and Hollins (1974):
- stems with slight symptoms present one or more lesions occupying in total less than half the circumference of the stem;
- stems with moderate symptoms present one or more lesions occupying at least half the circumference of the stem ;
- stems with severe symptoms are completely girdled by lesions; tissue softened.

- The driving functions for Fusarium stem rot [$FST_{1,2)}$ = function(DVS)] are built from assessments at different dates of the percentage of tillers with slight (FST1) and severe symptoms (FST2).

These two levels of symptoms are described by Smiley et al. (2005):
- stems with slight symptoms present tillers with browning up to the second node;
- stems with severe symptoms present tillers with browning up to the third node or above.

- The driving function for fusarium head blight [FHB = function(DVS)], is computed from assessments of the percentage of kernels diseased by Fusarium Head blight (FHB) at different dates.

- The driving functions for leaf diseases are of the same general shape: X = function(DVS). These are derived from assessments at different dates of the percentage of diseased leaf area due to Septoria nodorum blotch (X = SN) or Septoria tritici blotch (X = ST) or Brown rust (X = BR) or Yellow rust (X = YR) or Powdery mildew (X = PM).

3.2. A standardised protocol of data collection

In this section, we provide a standardised protocol for data collection, which could be shared by different research teams. At this stage, this should be considered as a draft only, which is open to suggestions or discussions.

3.2.1. Timing of assessments

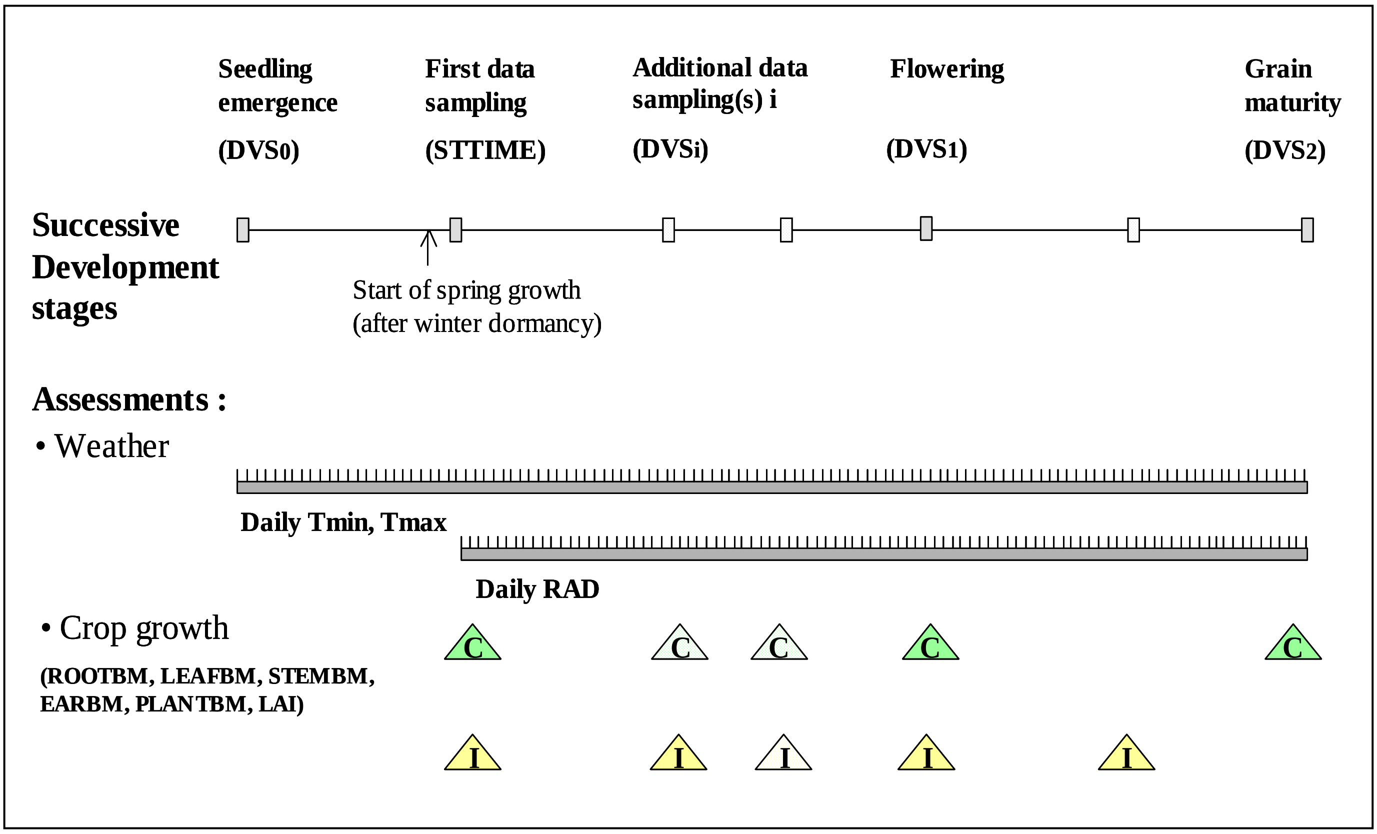

Figure 9. Timing of assessments.

Date of injuries (I) or crop growth (C) assessments. The field (coloured) triangles represent the minimal assessment date and the empty triangle represent the additional date of sampling.

Successive Development stage for the different events and assessments (climatic data, samplings). The field (coloured) rectangles represent the minimal assessment date and the empty triangles represent additional d of sampling.

3.2.2. Weather data

The daily minimum temperature (Tmin) and maximum temperature (Tmax) will be recorded from the date of seedling emergence until the crop maturity. Temperature data (1) will be used to compute $SUMT_0$ (initial sum of temperature at STTIME), (2) will be used as daily input for the simulation, and (3) will be used to compute the SUMT at each data sampling into build the different driving functions.
The daily global radiation (RAD) will be recorded since the first data collection until crop maturity. These data will be used (1) as daily input for the simulation and (2) can be used to build the RUE driving function.

3.2.3. Monitoring of development stage

The date (Julian day) of appearance of the following development stage will be monitored and used to build the DVS driving function. These data will be reported in the reporting form RF1 (Annex 4).
- seedling emergence (DVS0):
Development stage description: emergence of the first leaf observed on the ***majority*** of plants (more than 50%).
- flowering (DVS1):
Stage description: After stem elongation, the head emerge out of the flag leaf sheath. Within a few days after heading, flowering (pollination) begins. Flowering takes place when extrusion of the anthers from each floret are observed in 50% of heads on a given area (Gate, 1995).

- grain maturity (FINTIME; DVS2):
Stage description: When the kernel approaches maturity, its consistency becomes "hard dough." At physiological maturity, the glumes and peduncle are no longer green and little green colouring remains in the plant. The kernel has reached its maximal dry weight and it cannot be any more split by the nail.

3.2.4. Crop growth assessments (destructive samplings)

The first data sampling will occur in the few days following the start of spring growth, i.e., at the onset of growth after winter dormancy. The next samplings should be done at flowering and grain maturity. As much as possible, additional samplings should be made before flowering and between flowering and grain maturity (Fig.9). Data collected at these samplings are:
- the dry biomass of living leaves (LEAFBM);
- the dry biomass of dead leaf (SENLBM);
- the leaf area index of living leaves (LAI);
- the dry biomass of stems (STEMBM);
- the dry biomass of ears (EARBM);
- and the dry biomass of roots (ROOTBM).

3.2.5. Assessments of injuries caused by pests

The assessments of injuries will be done in the field as often as possible (Fig. 9). These data will produce a description of the dynamics of injuries during crop growth (see Section 1.2.2). Table 6 presents a summary of the different injuries or pests to be assessed and the type of assessment (destructive or non destructive).

Abbreviation	Definition	Type of measurement
WD	Dry biomass of weeds	Destructive sampling with weeds uprooting
TAK	Percentage of take-all disease on roots.	Destructive sampling with wheat uprooting
APH	Number of aphids	Observation on plant level
EYS	percentages of tillers with eyespot	Observation on stems
SHY	percentages of tillers with sharp eyespot symptoms	Observation on stems
FST	percentages of tillers with Fusarium stem rot symptoms.	Observation on stems
FHB	percentage of kernels with Fusarium head blight symptoms	Observation on ears
SN	Septoria nodorum blotch severity	Observation on leaves
ST	Septoria tritici blotch severity	Observation on leaves
BR	Brown rust severity	Observation on leaves
YR	Yellow rust severity	Observation on leaves
PM	Powdery Mildew severity	Observation on leaves
BYDV	Percentages of plants with Barley Yellow dwarf Viruses symptoms	Observation on leaves

Table 6. Monitoring of injuries.

The Processing of the data acquisition is described in Section 2.2.3. These data (assessment and timing) will be recorded in the recording forms RF1-3 (Annex 4).

3.2.6. Observational unit

We provide here an example of one observational unit which has shown to be practical to repeat (3-10 repetitions) in commercial fields as well as in experimental trials (Bruno Mille, unpublished results).

This observational unit (Fig. 10) includes several sampling zones ('plots' numbered one to five; approximately 0,5m² per plot) and a walking zone and buffer areas surrounding each plot. Buffer areas are used as “compensation buffer”: when samples are taken away from a sampling zone, plants in the neighbouring units have tended to grow more than plants in units that would be part of a homogeneous stand. The buffer area therefore protects plots from sampling interferences on crop growth.

Each plot is used to assess crop growth, weed biomass, and pests injuries at a different development stages (plot 1 for the first data collection, plots 2 and 3 for data collections before flowering, plot 4 for data collection at flowering and plot 5 for data collection after flowering and at harvest) (see Section 2.1). At each assessment, a minimum of 5 plants are observed and sampled (for injuries and crop growth assessments) from the appropriate plot. These plants need to be carefully chosen to represent the overall status of the plot. Weeds are also sampled on the half area of the plot (0.25m²). The sampled plants (wheat and weeds) are uprooted, placed in bags, and processed rapidly (description in the following sections).

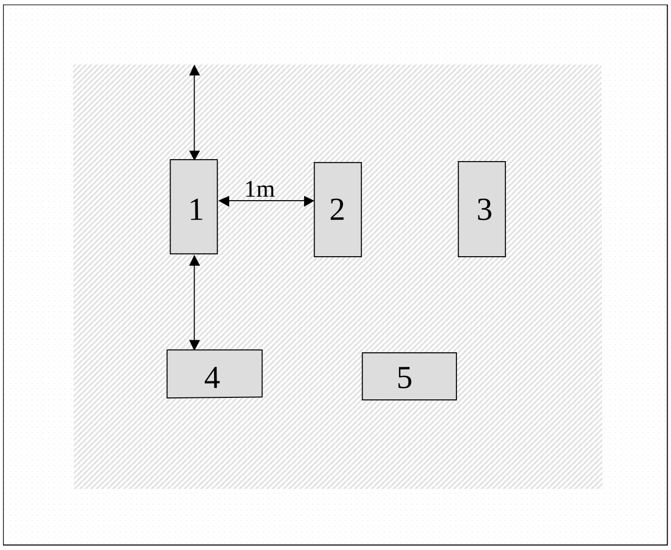

Figure 10. Example of the structure of one observational unit.
☐ Walking zone
☐ Buffer area
☐ Sampling zone (plot 1 = first sampling zone to plot 5 = last sampling zone)

3.2.7. Assessments of injuries and crop growth

Crop density (D), i.e. the number of plants per m², needs to be assessed and is used to convert the following assessments to 1 m² of a crop stand.

The following operational definitions are being used:

- development stage: stage of development that has been reached by the majority (more than 50%) of the plants in a given plot.
- leaf (or living leaf): leaf with at last 50% green area (i.e. without yellow or yellowing parts = colour between green and yellow).
- dead leaf: leaf with at least 50% yellow or yellowing parts

3.2.7.1. Assessment of injuries

- Weeds: after root washing, weeds are placed in paper bag, oven-dried and weighed The dry biomass of weeds per square meter (WD) will be computed by:

$$WD = \frac{\text{dry biomass of weeds on } 0.25\text{m}^2}{0.25}$$

- BYDV: the number of diseased plant affected by the Barley Yellow Dwarf viruses is assessed on the total plot (0.5m²). The percentage of diseased plants (BYDV) is then estimated as:

$$BYDV = \frac{PLANTNB_{BYDV}}{PLANTNB}$$

$PLANTNB_{BYDV}$ = number plants with virus symptoms
PLANTNB = number of plants observed

- Take-all: assessment of take-all requires destructive root samplings. Five plants are uprooted (these plants can also be used for crop growth assessments, see Section 2.3.2), and their roots washed under tap water to assess take-all severity. Take-all severity (TAK) is expressed as a percentage of diseased root length.

- The following assessments are made on five plants. These do not require destructive sampling but are also preferably done on plants sampled to assess crop growth.

- The number of aphids (S. Avenae only) is assessed and the total number of aphids per square meter (APH) is computed by:

$$APH = \frac{\text{number of aphids on observed plants}}{\text{number of plants observed}} \times D$$

Where D = plant density (number of plants per square meter).

- The percentage of tillers with slight, moderate and severe Eyespot (EYE) and Sharp Eyespot symptoms (SHY), and the percentage of tillers with slight and severe Fusarium Stem Rot symptoms (FST) are assessed on each plant following the scales described in Section 1.2.2.

- The percentage of kernels with Fusarium Head blight (FHB) symptoms is visually assessed on each plant.

- Diseases on leaves (septoria sodorum blotch, septoria tritici blotch, brown rust, yellow rust, and powdery mildew) are assessed on the living leaves of the main tiller of each plant. The severity of each disease corresponds to a percentage of leaf area, which can be assessed with scales such as those developed by Large (1954).

3.2.7.2. Measurements of crop growth and yield

After sampling, roots are washed in tap water to remove the soil particles (roots can be cut for this process but only in the ground level zone). Samples are to be kept in coolers or transferred to a cold room until processing (this period should not exceed 2 days).

The different organs of the sampled plants (i.e., roots, stems, living leaves, dead leaves and ears) are separated (the leaves are cut at the ligule level). First, the total area of the living leaves should be assessed with a leaf area meter so as to assess the LAI. The LAI can also be estimated by a relationship between the leaf length and width.
All organs are then put in paper bags for oven drying (2-3 days at 70℃ until dry) and will be weighted separately.

The dry biomass (g.m-^{2}) is estimated as:

$$ROOTBM = \frac{\text{total dry biomass of roots of sampled plants}}{\text{number of plants sampled}} \times D$$

$$LEAFBM = \frac{\text{total dry biomass of living leaves on sampled plants}}{\text{number of plants sampled}} \times D$$

$$SENLBM = \frac{\text{total dry biomass of dead leaves on sampled plants}}{\text{number of plants sampled}} \times D$$

$$STEMBM = \frac{\text{total dry biomass of stems on sampled plants}}{\text{number of plants sampled}} \times D$$

$$EARBM = \frac{\text{total dry biomass of ears on sampled plants}}{\text{number of plants sampled}} \times D$$

$$PLANTBM = ROOTBM + LEAFBM + SENLBM + STEMBM + EARBM$$

Where D = plant density (number of plants per square meter).
ROOTBM = dry biomass of roots
LEAFBM = dry biomass of living leaves
SENLBM = dry biomass of dead leaves
STEMBM = dry biomass of stems
EARBM = dry biomass of ears
PLANTBM = total dry biomass of shoots

The specific leaf area (SLA) and the leaf area index (LAI) are estimated as:

$$SLA = \frac{\text{total living leaf area of sampled plants}}{\text{dry biomass of living leaves}}$$

$$LAI = \frac{\text{total living leaf area of sampled plants}}{\text{number of plants sampled}} \times D$$

At harvest, after ear weight measurements, ears will be threshed and the filled grain will be separated from rachis and unfilled grain. Then the filled grain will be weighted.

The actual yield (Y_{ACT}, g.m^{-2}) is estimated as:

$$Y_{ACT} = \frac{\text{dry biomass of filled grain of sampled plants}}{\text{number of plants sampled}} \times D$$

With D = plant density (number of plants per square meter).

3.3. Collection of additional data for the characterisation of production situations and injury profiles

Recording form RF1 (Annex 3) lists a number of attributes of the environment where the data collection and samplings are taking place. These attributes are meant to characterise the production situation under which the monitoring (and thus the modelling) is done. This information is needed to document the production situation where these measurements are being made, and compare results from one location to another. Accumulation of such information among sites and years would enable a formal analysis of the relationships between production situations and injury profiles. Such an analysis for winter wheat in Europe is lacking, and therefore, we do not yet have a framework where the outputs of simulation modelling can be interpreted.

More generally, this framework of relationships between production situations and injury profiles is also lacking to interpret the results of networked research, whether pertaining to standard epidemiological work, breeding research, or plant protection tools. Implementing RICEPEST in various research projects might therefore be a means to develop the necessary data set enabling such an analysis and the determination of this framework.

4. ANNEX 1. Model description.

WHEATPEST is a simple agrophysiological model which incorporates damage mechanisms (Rabbinge and Vereijken, 1980; Boote et al., 1983), that is, simulates the physiological effects of injury on crop growth and yield. The general structure of WHEATPEST is derived from RICEPEST, a model developed for rice yield loss analysis (Willocquet et al., 2000; 2002; 2004), and from a model developed by Johnson (1992) for potato multiple pests.

Parameters and variables used in the model are listed in Annexe 1b, and the model structure is shown in Figure A1. The program of the model is written in FST (Fortan Simulation Translator; Rappoldt & van Kraalingen 1996).

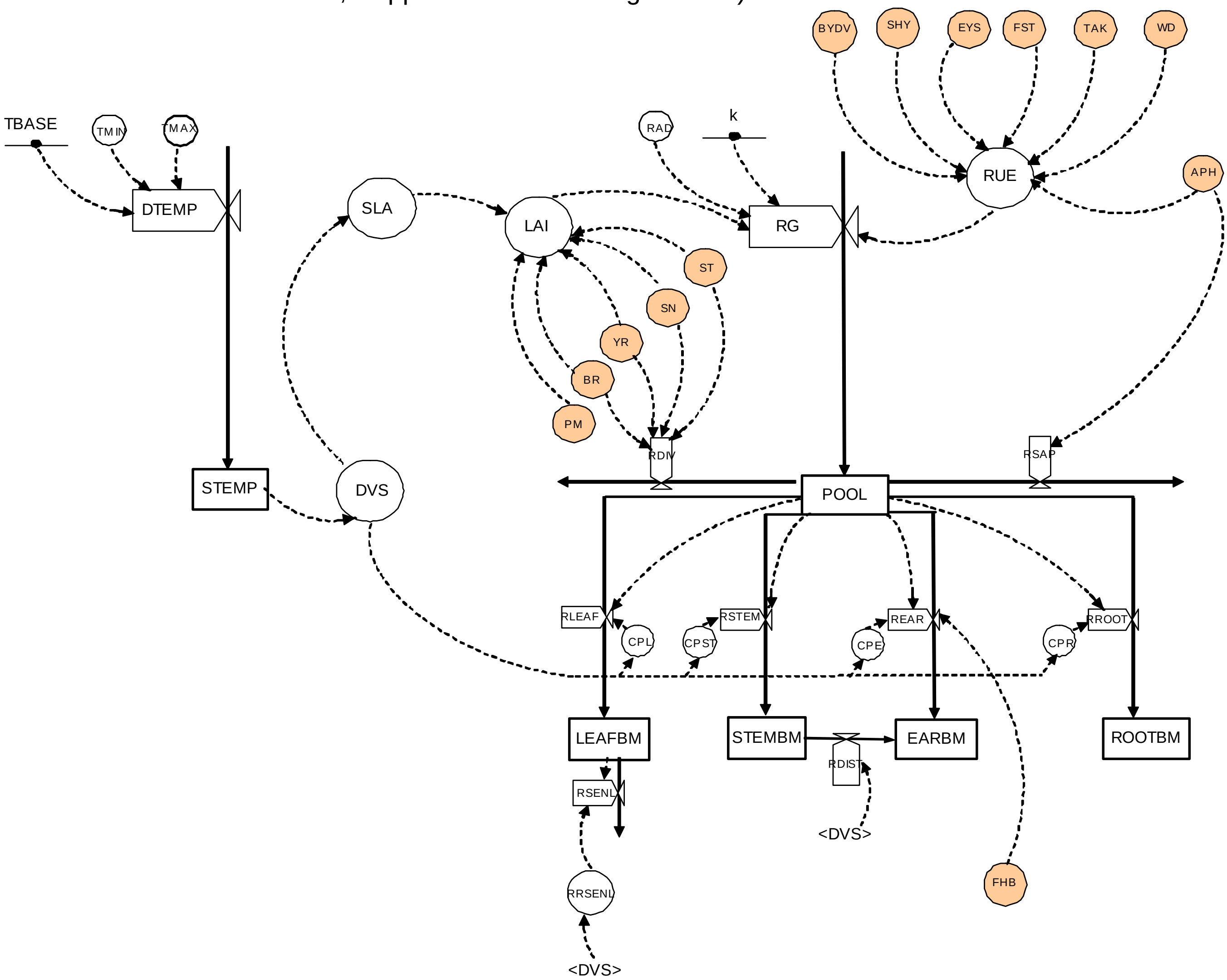

Figure A1. Schematic representation of the wheat crop growth model with coupling of damage mechanisms.

The time step of the model is one day and the system considered is 1m²of wheat crop. The simulation is initiated at the beginning of spring growth (after winter dormancy) and ends at crop maturity.

The model incorporates harmful effects of 13 different pests on wheat: weeds, aphids, viruses, brown rust, yellow rust, powdery mildew, Septoria tritici blotch, Septoria nodorum blotch, take-all, eyespot, sharp eyespot, Fusarium stem rot, and Fusarium head blight, on wheat crop physiology.

Inputs to the model consist of weather data (daily temperature and radiation) and drivers for production situation and for injury profile. The driver for production situation (Willocquet et al., 2004) includes an array of driving functions that vary over time (e.g., RUE), and a set of parameters. Similarly, the driver for injury profile consists of an array of driving functions or parameters that represent the dynamics (or the maximum levels) of individual injuries over the course of a cropping season. These combined injury time-courses represent the injury profile a given crop stand has been exposed to during its cycle.

Outputs of the model consist in a series of dynamic variables over time: development stage (DVS), dry biomass of organs, Leaf Area Index (LAI); and final yield.

4.1. Modelling attainable growth (RG_{ATT}) and yield (Y_{ATT})

4.1.1. Development stage

Development is expressed as development stage (DVS), a dimensionless variable having the value 0 at seedling emergence, 1 at flowering (DVS1) and 2 at maturity (DVS2) (Spitters et al., 1989). Development is operationally defined as the stage reached by the *majority* (more than 50%) of the plants in a crop stand at a given point in time.

Development stage is defined as a function of the sum of temperature (SUMT) above 0℃, which is the minimum temperature threshold for wheat cultivars (TBASE) (Gate 1995). The sum of temperature required for a crop to reach maturity depends on variety, weather conditions (Gates), and thus is expected to depend on production situations.
The temperature sum is computed as follows:

$$SUMT_{t+\Delta t} = SUMT_t + (DTEMP_t \times \Delta t) \quad (1)$$

With:

$$DTEMP_t = \max\left[\left(0, \left(TMAX_t + TMIN_t\right)/2\right) - TBASE\right] \quad (2)$$

Where TMIN and TMAX are the minimum and the maximum daily temperature respectively. The initial value of SUMT corresponds to the sum of temperature above TBASE between sowing and the day when simulation start. TBASE is estimated at 0℃ (Gate, 1995).

4.1.2. Biomass production

The attainable rate of growth (RG_{ATT}) is proportional to the radiation use efficiency (RUE), to the daily global solar radiation (RAD), and to the light intercepted by the crop canopy (Monteith, 1977):

$$RG_{ATT\,t} = \left[1 - \exp^{(-k \times LAI_t)}\right] \times RAD_t \times RUE_{DVS\,t} \quad (3)$$

Where $1-\exp^{(-k\times LAI)}$ is the proportion of light intercepted by the crop, following Beer's law (Monsi & Saeki, 1953), and *k* is the coefficient of light extinction in the canopy.

Leaf area index (LAI) is proportional to the dry weight of leaves (LEAFBM) (deWit et al., 1970; van Keulen and Seligman, 1987; in van Delben et al., 2001).

$$LAI_t = LEAFBM_t \times SLA_{DVS_t} \quad (4)$$

Where SLA is the specific leaf area (i.e., the leaf area per unit of dry matter).

SLA varies with the crop development stage (van Keulen and Seligman, 1987 in van Delben et al., 2001). Young leaves are thinner, and thus have a higher SLA than older leaves. It is therefore expected that SLA declines over time. SLA also depends on the crop stand physiology, and therefore varies among production situations (Tardieu et al., 1999; Van Delden et al.; 2000, in van Delben et al., 2001).

RUE accounts for the overall efficiency of a crop to convert intercepted light by photosynthetically active leaves into plant biomass. RUE thus embeds the efficiency of several processes: gross photosynthesis, respiration, transportation of photosynthates before on-site biosynthesis, and synthesis of complex molecules from photosynthates (proteins, lipids, polysaccharides, etc.). RUE depends on multiple factors, such as concentration of leaf N (Evans 1983), thus nitrogen fertilisation (Serrano et al., 2000; Olesen et al., 2000); water availability (Penning de Vries et al., 1989, Olesen et al., 2000); cultivars (Calderini et al., 1997); growing location (Muurinen and Peltonen-Sainio, 2005); and between and pre- and post-anthesis periods (Calderini et al., 1997). Therefore, RUE is expected to vary with development stage and production situations.

4.1.3. Partitioning of assimilates

Daily accumulated assimilates are partitioned towards the different organs of the plants. The daily rates of biomass partitioned to leaves, ears, stems and roots are named RLEAF, REAR, RSTEM and RROOT, respectively. These rates depend on partitioning coefficients:

$$RLEAF_t = RG_{ATT_t} \times CPL_{DVS_t} \times (1 - CPR_{DVS_t}) \quad (5)$$

$$REAR_t = RG_{ATT_t} \times CPE_{DVS_t} \times (1 - CPR_{DVS_t}) \quad (6)$$

$$RSTEM_t = RG_{ATT_t} \times CPS_{DVS_t} \times (1 - CPR_{DVS_t}) \quad (7)$$

$$RROOT_t = RG_{ATT_t} \times CPR_{DVS_t} \quad (8)$$

Where CPL, CPE, CPS, and CPR are the coefficients of partitioning of assimilates to the leaves, ears, stems and roots, respectively. CPL, CPE, and CPS represent the partitioning coefficients relative to the biomass partitioned above ground. CPR represents the coefficient of partitioning towards roots relative to the total wheat biomass.

It is assumed that the partitioning coefficients vary with the crop development stage and among production situations. In general, partitioning towards roots, stems and leaves occurs until flowering. From this stage onwards, all assimilates are partitioned towards the ears (Penning de Vries et al., 1989).

The increase in dry weight for the different organs is computed as follow:

$$LEAFBM_{t+\Delta t}=LEAFBM_t+(RLEAF_t\times\Delta t) \quad (9)$$

$$EARBM_{t+\Delta t}=EARBM_t+(REAR_t\times\Delta t) \quad (10)$$

$$STEMBM_{t+\Delta t}=STEMBM_t+(RSTEM_t\times\Delta t) \quad (11)$$

$$ROOTBM_{t+\Delta t}=ROOTBM_t+(RROOT_t\times\Delta t) \quad (12)$$

Grain yield is set to 85% of ear weight at harvest (Penning de Vries et al., 1989), thus the attainable yield (Y_{ATT}) is computed by:

$$Y_{ATTt}=0,85\times EARBM_t \quad (13)$$

4.1.4. Redistribution of reserves accumulated in the stems

A large fraction of carbohydrates are temporarily stored in stems during the vegetative phase, and redistributed to ears during the reproductive phase (DVS>1) (Penning de Vries et al., 1989). About 20% of wheat stem weight at flowering consists of remobilisable carbohydrates (Groot, 1987). The daily flow of biomass redistributed from stems to ears (RDIST) between DVS1 and DVS2 is computed as follow:

When DVS>1:

$$RDIST_t=MAXSTEM_t\times RRDIST_t \quad (14)$$

where MAXSTEM is the maximal dry biomass of stems.

$$MAXSTEM_{t+\Delta t}=MAXSTEM_t+(RG_t\times CPS_{DVS_t}\times(1-CPR_{DVS_t})\times\Delta t) \quad (15)$$

Prior to flowering (i.e., when DVS<1), $MAXSTEM_t$ = $STEMBM_t$. After flowering (i.e., DVS>1), CPS is set to 0 and MAXSTEM remains at the constant maximal value of STEMBM estimated at flowering.

RRDIST is the daily relative rate of biomass which is redistributed from stem reserves to ears between DVS1 and DVS2, that is, during the reproductive stage of the crop.

$$RRDIST_t=STEMDIST\times RDEV2\times DTEMP_t \quad (16)$$

STEMDIST is the fraction of biomass which is translocated to ear between DVS1 and DVS2, and RDEV2 represents the rate of development after anthesis

Equation 7 thus becomes:

$$RSTEM_t=RG_{ATT\,t}\times CPS_{DVS_t}\times(1-CPR_{DVS_t})-RDIST_t \quad (17)$$

And equation 6 becomes:

$$REAR_t=RG_{ATT\,t}\times CPE_{DVS_t}\times(1-CPR_{DVS_t})+RDIST_t \quad (18)$$

4.1.5. Leaf senescence

We operationally define a 'living' leaf as a leaf with at least 50% of green area. Conversely, a 'dead' leaf is defined as a leaf with at least 50% dead or infected area. Leaf senescence refers to the loss of capacity to carry out essential physiological processes and to the loss of green leaves biomass (embedded in the decrease of RUE and LEAFBM respectively).

The daily rate of leaf senescence (RSENL) is computed as follows:

$$RSENL_t = RRSENL_{DVS_t} \times LEAFBM_t \qquad (19)$$

where LEAFBM is the dry biomass of leaves.

RRSENL is the relative rate of leaf senescence, depending on DVS (Groot, 1987). Leaf senescence can be accelerated by environmental stresses (Benbella and Paulsen, 1998), including water stress (Yang et al., 2001), and nitrogen supply (Crafts-Brandner et al., 1998). RRSENL thus depends on production situations.

Equation 5 thus becomes:

$$RLEAF_t = (RG_{ATT\,t} \times CPL_{DVS_t} \times (1 - CPR_{DVS_t})) - RSENL_t \qquad (20)$$

4.2. Modelling of damage mechanisms due to different wheat pests

4.2.1. Aphids

Sitobion avenae, an aphid often found in cereals in Europe, affects growth of winter wheat by two mechanisms: 1) phloem sap, and 2) decrease in net photosynthesis due to honeydew deposition (Rossing, 1991).
Following the model of Rossing (1991, from data of Coster 1983, and Rabbinge and Coster, 1984), the daily rate of assimilate sapping by aphids (RSAP) can be estimated by:

$$RSAP_t = RRSAP_{DVS_t} \times APHBM_{DVS_t} \times APH_{DVS_t} \qquad (21)$$

Where RRSAP is the relative feeding rate (expressed in g of assimilate sapped per g of aphids per day). It depends on DVS (Rossing, 1991). APHBM is the fresh weight of an individual aphid and depends on DVS (Mantel et al., 1982). APH is the (dynamic) number of aphids per m^2 of wheat crop, which is also dependent on the development stage.
In the model, RSAP is withdrawn from the daily rate of growth (RG_{ATT}).

Honeydew deposition corresponds to 35% of the phloem sapped (Rossing, 1991; from data of Coster 1983, and Rabbinge and Coster, 1984). Thus, the daily rate of honeydew deposition (RHONEY) is computed by:

$$RHONEY_t = 0{,}35 \times RSAP_t \qquad (22)$$

Honeydew decreases the rate of carbon dioxide assimilation at light saturation, and increases the rate of dark respiration (Rossing, 1995). The maximum reduction is 2% per g of honeydew, which is achieved 15 days after honeydew deposition.

This process is translated by multiplying the RUE daily by a reduction factor (RF_{APH}) which is proportional to the accumulated honeydew dry weight (HONEY).

In the model, a daily rate of 1.5% average the increase of honeydew impact from zero to 15 days after deposition. After 15 days, this rate is maintained at a constant maximum rate of 2% (Rossing, 1991). The decrease in RUE cannot exceed 20%. Thus, the reduction factor is computed by:

$$RF_{APHt+\Delta t} = MAX(1-(HONEY_{t+\Delta t} \times 0{,}015);0{,}8) \quad (23)$$

with:

$$HONEY_{t+\Delta t} = HONEY_t + RHONEY_t \times \Delta t \quad (24)$$

4.2.2. Weeds

Weeds affect wheat growth through competition for light, nutrients, and water (Spitters, 1989). The overall effect of weeds on wheat physiology can be reflected as a reduction factor of RUE (RF_{WEED}), which depends on weed biomass (Willocquet et al., 2000).

$$RF_{WDt} = \exp^{-0{,}003 \times WD_{DVSt}} \quad (25)$$

Where WD is the dry biomass of weeds per m^2 of wheat crop.

4.2.3. BYDV

Barley Yellow Dwarf Viruses (BYDV) species are transmitted by aphids and occur in phloem cells (Wiese, 1991). Disruption of phloem functioning may imply reduction in water and nutrient uptake, and a reduction in photosynthesis efficiency. This mechanism is reflected by multiplying RUE by a reduction factor (RF_{BYDV}). Based on McKirdy et al. (2002) and Perry et al. (2000), the reduction factor for BYDV was set to:

$$RF_{BYDVt} = 1 - \frac{0{,}35 \times BYDV_{DVSt}}{100} \quad (26)$$

Where BYDV is the percentage of diseased plants.

4.2.4. Take-all

Take-all disease, caused by *Gaeumannomyces graminis* var. *tritici*, is characterized by lesions on roots that affect the phloem vessels (Clarkson et al., 1975), leading to a reduction of nitrogen uptake (Schoeny et al., 2003). Reduction in water uptake may also be hypothesized. Compensation for nitrogen uptake is possible, which depends on nitrogen availability in the neighbourhood of healthy roots (Schoeny et al., 2003). For the sake of simplicity, no compensation is considered here. Damage mechanisms (reductions of N and water uptake) for take-all are synthesized by multiplying RUE by a reduction factor, RF_{TAK}, which equals:

$$RF_{TAKt} = 1 - \frac{TAK_{DVSt}}{100} \quad (27)$$

Where TAK is the root disease severity defined as the percentage of diseased root length.

4.2.5. Eyespot

Eyespot, caused by *Oculimacula yallundae* and *O. acuformis* (formerly *Tapesia yallundae* and *T. acuformis*; anamorph: *Pseudocercosporella herpotrichoides*), infects outer leaf sheaths, and then penetrates successive leaf sheaths. After stem extension has begun, the fungus may colonise the stem itself (Fitt et al., 1988). Lesions on sheaths cause negligible damage as compared to lesions on stems (Fitt et al., 1988), and thus are not considered here. Infection has direct effects on host physiology: disturbance of water and nutrients movement through the base of stem; and an indirect lodging effect (Scott and Hollins, 1974; Fitt et al., 1988). Three types of damaged tillers with symptoms on stems can be distinguished (Scott and Hollins, 1974): (1) tillers with 'slight' symptoms on stems: one or more lesions occupying in total less than half the circumference of the stem; (2) tillers with 'moderate' symptoms on stems: one or more lesions occupying at least half the circumference of the stem; and (3) tillers with 'severe' symptoms on stems: stem completely girdled by lesions; tissue softened. The fraction of diseased tillers for each type of disease symptoms generally increases linearly from booting to maturity (Scott and Hollins, 1978). At harvest, Clarkson (1981), found 1.2, 12.5 and 35% yield losses on tillers with respectively slight, moderate, and severe eyespot symptoms. Based on these data, the direct effect of eyespot is summarized by reducing the RUE proportionally to the fraction of tillers with slight, moderate and severe symptoms with:

$$RF_{EYSt}=1-((0.03\times\frac{EYS1_{DVSt}}{100})+(0.28\times\frac{EYS2_{DVSt}}{100})+(0.78\times\frac{EYS3_{DVSt}}{100})) \quad (28)$$

Where RF_{EYS} is the reduction factor of RUE due to eyespot; EYS1, EYS2 and EYS3 are percentages of tillers with slight, moderate and severe eyespot symptoms, respectively.

The indirect effect of eyespot on crop, i.e., lodging, causes 15% of yield loss on tillers with severe symptoms (Scott and Hollins, 1974; Scott and Hollins, 1978). This is accounted for by decreasing ear dry biomass from DVS=1.8 to 2 (maturity), so as to achieve a 15% yield loss at maturity. The ear dry biomass reduced by lodging (REYS) is proportional to EARBM, which allows accounting for the interaction with other injuries that affect ear dry biomass (which reduce EARBM and thus the lodging impacts).

With DVS>1,8:

$$REYS_t=EARBM_t\times\left(\frac{EYS3_{DVSt}}{100}\times 0,017\right) \quad (29)$$

4.2.6. Sharp eyespot

Sharp eyespot, caused by *Rhizoctonia cerealis*, causes lesions on the stem base of wheat plants (Clarkson and Cook, 1983). It is assumed that sharp eyespot damage mechanisms are the same as those for eyespot, except for the lodging effect, which seldom occurs for this disease. At harvest, Clarkson and Cook (1983) found 2.8, 5.4, and 26.4% yield losses on tillers with respectively slight, moderate, and severe Sharp eyespot symptoms.

Based on these data, the reduction of RUE by Sharp eyespot is computed with:

$$RF_{SHYt}=1-((0.07\times\frac{SHY1_{DVSt}}{100})+(0.14\times\frac{SHY2_{DVSt}}{100})+(0.65\times\frac{SHY3_{DVSt}}{100})) \quad (30)$$

Where RF_{SHY} is the reduction factor of RUE due to sharp eyespot; SHY1, SHY2 and SHY3 are percentages of tillers with slight, moderate, and severe sharp eyespot symptoms, respectively.

4.2.7. Fusarium stem rot

Fusarium stem rot is associated to *Fusarium* species (mainly *Fusarium graminearum, F. culmorum*), and *Microdochium nivale* (Daamen et al., 1991), and causes roots, crown and lower nodes and internodes to turn brown (Wiese, 1991). As for eyespot and sharp eyespot, the damage mechanisms for this injury are reflected by reducing RUE. The magnitude of RUE reduction depends on the type of symptom: tillers with slight symptoms correspond to tillers with browning up to the second node; and tillers with severe symptom correspond to browning up to the third node or above. These categories of tillers correspond to (D1 and D2), and (D3 and D4) categories described by Smiley et al. (2005), and are associated with 11% and 29% yield losses, respectively (Smiley et al., 2005). Based on these data, the reduction of RUE by Fusarium stem rot is computed by:

$$RF_{FST\,t} = 1 - \left(\left(0.26 \times \frac{FST1_{DVS\,t}}{100}\right) + \left(0.67 \times \frac{FST2_{DVS\,t}}{100}\right)\right) \quad (31)$$

Where RF_{FST} is the reduction factor of RUE due to Fusarium stem rot; FST1 and FST2 are percentages of tillers with slight and severe Fusarium stem rot symptoms, respectively.

4.2.8. Fusarium Head Blight

Fusarium head blight (FHB) is associated in Europe with at least four *Fusarium* species (*Fusarium graminearum, F. culmorum, F. avenaceum*, and *F. poae*), and with *Microdochium nivale* (Parry et al., 1995). The fungi colonise grains and reduce yield. They also produce mycotoxins that are harmful to animals and humans, but this effect will not be considered here. It is hypothesized that the increase in grain dry biomass is reduced proportionally to the fraction of kernels infected by the fungi involved in FHB, by multiplying it by a reduction factor RF_{FHB}. The reduction parameter value (1.1) is derived from Mesterhazy et al. (2003; 2005), and RF_{FHB} is computed as:

$$RF_{FHB\,t} = 1 - (1.1 \times FHB_{DVS\,t}) \quad (32)$$

where FHB is the percentage of kernels diseased.

4.2.9. Leaf diseases

Lesions on leaves can affect crop physiology through four main mechanisms (Rabbinge and Vereijken, 1980; Boote et al., 1983; Savary et al., 1990):
(i) Foliar diseases cause lesions which decrease the photosynthetic area: photosynthesis does not occur on leaf parts covered by lesions;
(ii) Photosynthesis can also be decreased in areas surrounding lesions. This can be reflected by using the concept of virtual lesion (Bastiaans, 1991). A virtual lesion is the area including the visual lesion, and the symptomless zone around the visual lesion, where photosynthesis is impaired. For low fraction of virtual lesion (<20%), the fraction of photosynthetically active area can be written as $(1 - x)^{beta}$, where x is disease severity and beta represents the ratio of the virtual lesion area over the actual lesion area. The effect is introduced in the model as a fraction of reduction of the (green) LAI.
(iii) Assimilates can be diverted to the lesions for production of reproduction propagules;
(iv) Foliar lesions can cause an acceleration of leaf senescence.

4.2.9.1. Septoria nodorum blotch

Septoria nodorum blotch (*Septoria nodorum*) causes lesions which decrease the photosynthetic area. The effects on gross photosynthesis of lesions and senesced tissues surrounding lesions correspond to β_{SN} = 1 (Rooney, 1989; Scharen and Taylor, 1968).

A fraction of 22% of photosynthates is diverted to the lesions for the formation of pycnidia for diseased leaves with a severity of 35% (Scharen and Taylor, 1968). Assuming a linear relationship between disease severity and assimilate uptake for pycnidia formation, this is included in the model by reducing the quantity of assimilates produced daily as:

$$RDIVSN_t = RGATT_t \times (0{,}63 \times SN_{DVSt}) \quad (33)$$

Where RDIVSN is the daily rate of assimilate diversion, RG is the rate of crop growth, and SN is severity of *Septoria nodorum* blotch.

4.2.9.2. Septoria tritici blotch

Septoria tritici blotch (*Mycosphaerella graminicola*) causes lesions which decrease the photosynthetic area. The effects on gross photosynthesis of lesions and surrounding senesced tissues correspond to β_{ST} = 1.25 (Robert et al., 2006).
Diversion of assimilates for pycnidia production is included in the model in the same way as for Septoria nodorum blotch:

$$RDIVST_t = RGATT_t \times (0{,}63 \times ST_{DVSt}) \quad (34)$$

Where RDIVST is the daily rate of assimilate diversion, and ST is severity of *Septoria tritici* blotch.

4.2.9.3. Brown rust

Brown (leaf) rust is caused by *Puccinia triticina*. Lesions do not affect photosynthesis on symptomless leaf tissues, that is, a β_{BR} = 1 is used (Spitters et al., 1990; Robert et al., 2005). Daily carbohydrate uptake for spore production is proportional to the number of pustules (Mehta and Zadoks, 1970; Savary et al., 1990):

$$RDIVBR_t = 4.62 \times 10^{-6} \times NPUSBR_t \quad (35)$$

With:

$$NPUSBR_t = BR_{DVSt} \times \frac{LAI_t}{SURFBR} \quad (36)$$

Where NPUSBR is the number of pustules of brown rust per m^2 of wheat crop, BR is brown rust severity, SURFBR is the area of a pustule of leaf rust, and is set to 10^{-6} m^2.

4.2.9.4. Yellow rust

Yellow (stripe) rust, caused by *Puccinia striiformis*, causes lesions which decrease the photosynthetic area. The effects of lesions on maximum photosynthesis correspond to β_{YR} = 1.5 (Yang and Zeng, 1988).

Daily carbohydrate diverted for spore production is included in the same way as for brown rust:

$$RDIVYR_t = 4.62 \times 10^{-6} \times NPUSYR_t \quad (37)$$

With:

$$NPUSYR_t = YR_{DVSt} \times \frac{LAI_t}{SURFYR} \quad (38)$$

Where NPUSYR is the number of pustules of yellow rust per m^2 of wheat crop, YR is yellow rust severity, SURFYR is the area of a pustule of leaf rust, and is set to 10^{-6} m^2.

4.2.9.5. Powdery mildew

Powdery mildew (*Blumeria graminis*) causes lesions that decrease the photosynthetic area. The photosynthesis of the area surrounding the lesion is also impaired. The corresponding β value depends on the incident radiation, and increases as radiation increases (Rabbinge et al., 1985). As powdery mildew generally develops in the lower part of the canopy, a β_{PM} value corresponding to that fraction of the canopy was derived from Rabbinge et al. (1985), which is 2.5.

4.3. Modelling actual growth (RG$_{ACT}$) and yield (Y$_{ACT}$) and interaction between injuries

The combined effects of injuries on crop physiology are represented in WHEATPEST by the product of the corresponding reduction factors affecting a same variable.

Equation 4 thus becomes:

$$LAI_t = LEAFBM_t \times SLA_{DVSt} \times (1 - SN_{DVSt})^{\beta SN} \times (1 - ST_{DVSt})^{\beta ST} \times (1 - BR_{DVSt})^{\beta BR} \times (1 - YR_{DVSt})^{\beta YR} \times (1 - PM_{DVSt})^{\beta PM} \quad (39)$$

where the reduction factors for LAI due to the different leaf pathogens are thus multiplied.

The model therefore assumes that one pathogen does not affect a leaf area that has already been injured by another one (Johnson, 1990), as in the case e.g., of bean rust and anthracnose (Lopes and Berger, 2001), and of wheat leaf rust and Septoria tritici blotch (Robert et al., 2004). The multiplication of reduction factors also assumes that injuries are spatially distributed randomly. Less-than-additive damage interactions between pests sharing the same damage mechanisms are thus modelled.

Eq.3 becomes:

$$RG_{ACTt} = \left[1 - \exp^{(-k \times LAI_t)}\right] \times RAD_t \times RUE_{DVSt} \times RF_t \times DIVF_t - RSAP_t \quad (40)$$

With:

$$DIVF_t = \left(1 - \frac{RDIVSN_t}{RG_{ATTt}}\right) \times \left(1 - \frac{RDIVST_t}{RG_{ATTt}}\right) \times \left(1 - \frac{RDIVBR_t}{RG_{ATTt}}\right) \times \left(1 - \frac{RDIVYR_t}{RG_{ATTt}}\right) \quad (41)$$

Where DIVF = diversion factor which take account for interactions between injuries.

And with:

$$RF_t = RF_{APHt} \times RF_{WDt} \times RF_{BYDVt} \times RF_{TAKt} \times RF_{EYSt} \times RF_{SHYt} \times RF_{FSTt} \quad (42)$$

Eq.18 becomes:

$$REAR_t = \left[RG_t \times CPE_{DVS\,t} \times (1 - CPR_{DVS\,t}) + RDIST_t\right] \times RF_{FHB\,t} - REYS_t \quad (43)$$

Finally, the actual yield is computed as follows :

$$Y_{ACTt} = 0{,}85 \times EARBM_t \quad (44)$$

5. ANNEX 2. Variables and parameters used in WHEATPEST.

Name	FST Code	Definition	Units	Reference, equation or parameter value
A. Daily climatic data entry				
RAD	RAD	Daily global sun radiation	$MJ.m^{-2}.day^{-1}$	
TMIN	TMIN	Daily minimum temperature	C	
TMAX	TMAX	Daily maximum temperature	C	
B. State variables, initial values				
STTIME	STTIME	Julian day of beginning of simulation	Julian day	
FINTIM	FINTIM	Julian day of end of simulation	Julian day	
$EARBM_0$	EARWI	Initial value of dry ears biomass	$g.m^{-2}$	
$LEAFBM_0$	LEAFWI	Initial value of dry green leaves biomass	$g.m^{-2}$	
$ROOTBM_0$	ROOTWI	Initial value of dry roots biomass	$g.m^{-2}$	
$STEMBM_0$	STEMWI	Initial value of dry stems biomass	$g.m^{-2}$	
$MAXSTEM_0$	MAXSTI	(= $STEMBM_0$). Initial value of dry stems biomass used for estimation of maximal dry stems biomass when DVS>1.	$g.m^{-2}$	
$SUMT_0$	STEMPI	Sum of temperature above the threshold 0℃ for wheat between emergence and beginning of simulation.	C.day	
C. Parameters for crop				
k	K	Coefficient of light extinction	-	0.65 (Monteith, 1969)
TBASE	TBASE	Temperature threshold for wheat growth	C	0 (Gates, 1995)
STEMDIST	FRDIST	Fraction of stem dry biomass translocated to ears between DVS1 and DVS2	-	20% (Groot, 1987)
D. Parameters for injuries				
SURFBR	SURFLR	Leaf area of a pustule of brown rust	m²	10^{-6}
SURFYR	SURFSR	Leaf area of a pustule of yellow rust	m²	10^{-6}
β_{SN}	-	Ratio of the virtual lesion area over the actual lesion area for Septoria nodorum blotch	-	1. (Rooney, 1989; Scharen and Taylor, 1968)
β_{ST}	BETSTB	Ratio of the virtual lesion area over the actual lesion area for Septoria tritici blotch	-	1.25 (Robert et al., 2006).
β_{BR}	-	Ratio of the virtual lesion area over the actual lesion area for Brown rust	-	1 (Spitters et al., 1990; Robert et al., 2005)
β_{YR}	BETASR	Ratio of the virtual lesion area over the actual lesion area for Yellow rust	-	1.5 (Yang and Zeng, 1988).
β_{PM}	BETAPM	Ratio of the virtual lesion area over the actual lesion area for powdery mildew	-	2.5, derived from Rabbinge et al. (1985)

Name	FST Code	Definition	Units	Reference, equation or parameter value
E. Generic driving functions for wheat attainable growth				
DVS	DVS	Development stage related to the temperature sum above a threshold TBASE. Driver [=f(STEMP)]	-	
SLA	SLA	Specific Leaf Area . Driver [=f(DVS)]	$m^2.g^{-1}$	
RUE	RUE	Radiation Use Efficiency. Driver [=f(DVS)]	$g.MJ^{-1}$	
CPL	CPL	Coefficient of partitioning in leaves within shoots (total leaves). Driver [=f(DVS)]	-	
CPS	CPS	Coefficient of partitioning in stems within shoots. Driver [=f(DVS)]	-	
CPE	CPE	Coefficient of partitioning in ears within shoots. Driver [=f(DVS)]	-	
RDEV	RDEV	Rate of development per degree. Driver [=f(DVS)]	$day^{-1}.C^{-1}$	
RRSENL	RRSENL	Daily relative rate of leaf senescence. Driver [=f(DVS)]	day^{-1}	
F. Generic driving functions for injuries				
APHBM	SFWAPH	Fresh biomass of an individual aphid. Driver [=f(DVS)]	$g.aphids^{-1}$	
RRSAP	RRSAP	Daily relative feeding rate of aphids. Driver [=f(DVS)]	day^{-1}	
APH	APHNB	Number of aphids per m^2 of wheat crop. Driver [=f(DVS)]	$aphids.m^{-2}$	
BYDV	100*BYDV	Percentages of diseased plants. Driver [=f(DVS)]	%	
TAK	100*SEVTA	Root disease severity defined as the percentage of diseased root length. Driver [=f(DVS)]	%	
WD	WEED	Dry biomass of weeds per m^2 of wheat crop. Driver [=f(DVS)]	$g.\ m^{-2}$	
ST	STB	Septoria tritici blotch severity (between 0 and 1). Driver [=f(DVS)]	-	
SN	SNB	Septoria nodorum blotch severity (between 0 and 1). Driver [=f(DVS)]	-	
BR	LR	Brown rust severity (between 0 and 1). Driver [=f(DVS)]	-	
YR	SR	Yellow rust severity (between 0 and 1). Driver [=f(DVS)]	-	
PM	PM	Powdery Mildew severity (between 0 and 1). Driver [=f(DVS)]	-	
FHB	FHB	percentage of kernels diseased. Driver [=f(DVS)]	%	
EYS1	100*ES1	percentages of tillers with slight eyespot symptoms. Driver [=f(DVS)]	%	
EYS2	100*ES2	percentages of tillers with moderate eyespot symptoms. Driver [=f(DVS)]	%	
EYS3	100*ES3	percentages of tillers with severe eyespot symptoms. Driver [=f(DVS)]	%	
SHY1	100* SES1	percentages of tillers with slight sharp eyespot symptoms. Driver [=f(DVS)]	%	
SHY2	100*SES2	percentages of tillers with moderate sharp eyespot symptoms. Driver [=f(DVS)]	%	
SHY3	100*SES3	percentages of tillers with severe sharp eyespot symptoms. Driver [=f(DVS)]	%	
FST1	100*BFR1	percentages of tillers with slight Fusarium stem rot symptoms. Driver [=f(DVS)]	%	
FST2	100*BFR2	percentages of tillers with severe Fusarium stem rot symptoms. Driver [=f(DVS)]	%	

Name	FST Code	Definition	Units	Reference, equation or parameter value
Variables computed in the model :				
Degree days above the thermal threshold				
SUMT	STEMP	Sum of temperature above a threshold temperature (TBASE)	C.day	Interim variable. Eq.1
DTEMP	DTEMP	Daily rate of increase in temperature sum above a threshold TBASE	C	Interim variable. Eq.2
Daily accumulation of biomass				
RG_{ATT}	RGATT	Attainable daily rate of growth	$g.m^{-2}.day^{-1}$	Interim variable. Eq.3
RG_{ACT}	RG	Actual daily rate of growth	$g.m^{-2}.day^{-1}$	Interim variable. Eq.40
LAI	LAI	Leaf Area Index	-	Interim variable. Eq.4 & 39
DIVF	-	Reduction factor of RUE due to interaction between injuries (SN, ST, BR and YR) which daily diverted assimilate	-	Interim variable. Eq.41
RFi	-	Reduction factor for RUE caused by injury i	-	Interim variable. Eq.42
RF_{BYDV}	RFBYDV	Reduction factor of RUE due to BYDV	-	Interim variable. Eq.26
RF_{WD}	RFWEED	Reduction factor of RUE due to weeds	-	Interim variable. Eq.25
RF_{TAK}	RFTA	Reduction factor of RUE due to Take-all.	-	Interim variable. Eq.27
RF_{APH}	RFAPH	Reduction factor of RUE due to aphids	-	Interim variable. Eq.23
HONEY	HONEY	mass of accumulated honeydew	$g.m^{-2}$	Interim variable. Eq.24
RHONEY	RHONEY	daily rate of honeydew accumulated	$g.m^{-2}.day^{-1}$	Interim variable. Eq.22
RSAP	RSAP	Daily rate of assimilate sapping by aphids	$g.m^{-2}.day^{-1}$	Interim variable. Eq.21
RDIVST	(1-RFSTDV)*RGATT	daily rate of assimilate diversion due to Septoria tritici blotch	$g.m^{-2}.day^{-1}$	Interim variable. Eq.34
RDIVSN	(1-RFSNDV)*RGATT	daily rate of assimilate diversion due to Septoria nodorum blotch	$g.m^{-2}.day^{-1}$	Interim variable. Eq.33
RDIVBR	RUPLR	daily rate of assimilate diversion due to brown rust	$g.m^{-2}.day^{-1}$	Interim variable. Eq.35
NPUSBR	NPUSLR	number of pustules of brown rust per m² of wheat crop	Nbpustules. m^{-2}	Interim variable. Eq.36
RDIVYR	RUPSR	daily rate of assimilate diversion due to yellow rust	$g.m^{-2}.day^{-1}$	Interim variable. Eq.37
NPUSYR	NPUSSR	number of pustules of yellow rust per m² of wheat crop	Nbpustules. m^{-2}	Interim variable. Eq.38
RF_{EYS}	RFES	Reduction factor of RUE due to Eyespot	-	Interim variable. Eq.28
RF_{SHY}	RFSES	Reduction factor of RUE due to Sharp Eyespot	-	Interim variable. Eq.30
RF_{FST}	RFBFR	Reduction factor of RUE due to Fusarium stem rot (brown foot rot)	-	Interim variable. Eq.31
Dry weight of leaves				
LEAFBM	LEAFW	Dry biomass of green leaves	$g.m^{-2}$	Interim variable. Eq. 9
RLEAF	RLEAFW	Daily rate of increase in green leaf dry biomass	$g.m^{-2}.day^{-1}$	Interim variable. Eq 20
RSENL	RSENL	Daily rate of leaf senescence	$g.m^{-2}.day^{-1}$	Interim variable. Eq.19

Name	FST Code	Definition	Units	Reference, equation or parameter value
Dry weight of stems				
STEMBM	STEMW	Dry biomass of stems	$g.m^{-2}$	Interim variable. Eq.11
RSTEM	RSTW	Daily rate of increase in stem dry biomass	$g.m.day^{-1}$	Interim variable. Eq.16
RDIST	RDIST	Daily rate of biomass redistributed from stems reserves to ears	$g.m.day^{-1}$	Interim variable. Eq 13
MAXSTEM	MAXST	Maximal dry biomass of stems	$g.m^{-2}$	Interim variable. Eq 15
RRDIST	RDIST/MAXST	Daily relative rate of biomass redistributed from stems reserves to ears	day^{-1}	Interim variable. Eq 16
Dry weight of ears				
EARBM	EARW	Dry biomass of ears	$g.m^{-2}$	Interim variable. Eq.10
REAR	REARW	Daily rate of increase in ear dry biomass	$g.m^{-2}.day^{-1}$	Interim variable. Eq 43
REYS	-	ear dry biomass reduced by lodging (severe eyespot symptoms) when DVS>1,8	$g.m^{-2}.day^{-1}$	Interim variable. Eq.29
RF_{FHB}		Reduction factor of REAR due to Fusarium Head Blight.	-	Interim variable. Eq.32
Dry weight of roots				
ROOTBM	ROOTW	Dry biomass of roots	$g.m^{-2}$	Interim variable. Eq.12
RROOT	RROOTW	Daily rate of increase in root dry biomass	$g.m^{-2}.day^{-1}$	Interim variable. Eq. 8
Yield				
Y_{ATT}	YIELD	Attainable Yield	$g.\ m^{-2}$	Output variable. Eq.13 & 44
Y_{ACT}	YIELD	Actual yield	$g.\ m^{-2}$	

6. ANNEX 3. Listing of the FST program for the wheat yield loss simulation model.

In this example, we present the data used for the PS1*IP1 simulation presented in Part 1 of the text.

```
* Crop growth model for winter wheat with damage mechanisms coupling functions
for wheat pests (diseases, insects, weeds)
* Damage mechanisms included: aphids, weeds, BYDV, take-all, eyespot,
* sharp eyespot, Fusarium stem rot, head blight, Septoria nodorum blotch,
* Septoria tritici blotch, brown rust, yellow rust, Powdery mildew
* Structure based on RICEPEST (Willocquet et al., 2000;2002;2004)
* System: population of tillers in 1 m2 of wheat field
* Time step: 1 day
* Simulation of the dynamics of :
* 1.development stage
* 2.biomass in the different organs of the plant
* The simulation starts at the end of winter and ends at crop maturity
* Run 0: simulation of attainable growth
* Run 1 to 14: simulation of damage due to various injuries

*Injury driver and crop drivers correspond to the PS1*IP1 example presented in
*the part 1 of the text.
*Attainable yield = 900g/m²
```

```
TITLE WHEATPS1

MODEL

INITIAL

*A. Switchers
*switcher for daily weather data, actual (-1), or parameter(+1)
PARAM SWIWTH  =1.

*B. State variables, initial values
*dry weight of roots                        g
INCON ROOTWI  =5.
*dry weight of green leaves                    g
INCON LEAFWI  =10.
*dry weight of stems                        g
INCON STEMWI  =6.
*dry weight of stems for maximum STEMW variable          g
INCON MAXSTI  =6.
*dry weight of ears (incon=0)                   g
INCON EARWI  =0.
*initial weight of honeydew                    g
INCON HONI  =0.
*sum of temperatures above the treshold (OøC)         C.day
*for wheat between emergence and beginning of simulation
*Simulation starts when spring growth starts, that is in this
*example, when temperature sum is 624 C.day
INCON STEMPI  = 624.

*C. Parameters for crop
*coefficient of light extinction (constant)(=0.65, Monteith, 1969)
PARAM K    =0.65
```

```
*Fraction of stem dry weight translocated to ear between DVS1 and DVS2 (=20% for
*wheat, Groot, 1987)
PARAM FRDIST  =0.2
*Temperature threshold for wheat growth (constant)         C
PARAM TBASE  =0.
*rate of development per degree after anthesis
*RDEV2=1/(temperature sum between DVS1 and DVS2)
RDEV2     =0.0011

*D. Parameters for injuries
*Beta for Septoria Tritici blotch
PARAM BETSTB=1.25
*Beta for powdery mildew
PARAM BETAPM=2.5
*Beta for stripe rust
PARAM BETASR=1.5

*E. Driving functions for injuries due to aphids
*SFWAPH=Specific Fresh Weight of Aphid, fresh weight of one aphid
*function of DVS (Mantel et al., 1982)
FUNCTION SFWAPT=0.,0., 0.9,0.000316, 1.,0.000316, 1.45,0.00025, ...
    1.75,0.000415, 2.1,0.000415
*RRSAP=relative rate of sapping (g of phloem sap dry weight per g
* of aphid fresh weight per day), function of DVS (Rossing, 1991)
FUNCTION RRSAPT=0.,0.45, 1.,0.45, 1.22,0.45, 1.45,0.32, 1.6,0.17, ...
    1.7,0.24, 2.1,0.24

*F. Parameters to simulate injury profiles
PARAM PAPH=0., PBYDV=0., PTA=0., PWEED=0., PSTB=0.,PLR=0.
PARAM PFHB=0., PPM=0.,PES=0.,PSR=0.,PSNB=0.,PSES=0.,PBFR=0.

*G. Simulation run specifications
*simulation ends at crop maturity (DVS=2)
FINISH DVS > 2.
*STTIME = julian day of beginning of simulation
TIMER STTIME = 74., FINTIM = 365., PRDEL=1.,DELT=1.

TRANSLATION_GENERAL DRIVER='EUDRIV'

DYNAMIC

*1.Tables for drivers for crop and injuries

*1.1 Generic driving functions for wheat attainable growth

*development stage related to the temperature sum above threshold
*1600 required from emergence to flowering (Gate,1995)
*910 required from flowering to maturity (Spitters et al., 1989)
FUNCTION DVST =0., 0., 1600.,1., 2510.,2., 2520.,2.1
*radiation use efficiency related to development stage
Attainable yield =900g/m² for PS1
FUNCTION RUET =0.,1.29, 0.9,1.29, 1.1,1.19, 2.1,1.19
*coefficient of partitioning in stems within shoots related to DVS
FUNCTION CPST =0.,0.35, 0.1,0.35, 0.25,0.3, 0.5, 0.5,...
        0.7,0.85, 0.95,1., 1.05,0., 2.1,0.
*coefficient of partitioning in leaves within shoots related to DVS
FUNCTION CPLT =0.,0.65, 0.1,0.65, 0.25,0.7, 0.5,0.5, 0.7,0.15,...
        0.95,0., 2.1,0.
*coefficient of partitioning in roots related to development stage
FUNCTION CPRT =0.,0.5, 0.1,0.5, 0.2,0.4, 0.35, 0.22, 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, 1.1,0.01, 1.2,0., 2.1,0.
*Specific leaf Area (m2.g-1) related to DVS
FUNCTION SLAT =0.,0.037, 1.,0.018, 2.,0.017, 2.1,0.017
* relative rate of leaf mortality, related to DVS (van Keulen et al.,1982)
FUNCTION RRSENT =0.,0., 1.,0., 1.2,0.01, 1.6,0.04, 1.8,0.1, 2.1,0.1

*1.2 Generic driving functions for injuries

*APHNBT: number of aphids per m2
* peak=0.58 aphids/tiller, 500 tillers/m2 so 290 aphids/m2
FUNCTION APHNBT=0.,0.,0.9,0., 1.,30., 1.5,125., ...
        1.76,250., 1.92,0., 2.1,0.

*BYDVT: fraction of plants diseased by BYDV (between 0 and 1)
FUNCTION BYDVT=0.,0.01,2.1,0.01

*SEVTAT: severity of take-all (between 0 and 1)
FUNCTION SEVTAT=0.,0., 0.3,0., 0.8,0.01, 1.6,0.05, 2.1,0.05

*WEEDT: weeds dry matter (/m2)
FUNCTION WEEDT=0.,0., 0.3,0., 1.6,10., 2.1,10.

*STBT:severity of septoria tritici blotch (between 0 and 1)
FUNCTION STBT=0.,0., 0.4,0., 0.8,0.0001, 1.6,0.001, 2.1, 0.001

*SNBT: severity of Septoria nodorum blotch (between 0 and 1)
FUNCTION SNBT=0.,0., 0.4,0., 0.8,0.00005, 1.6,0.0005, 2.1,0.0005

*LRT: severity of leaf rust (between 0 and 1)
FUNCTION LRT=0.,0., 0.4,0., 0.8,0.000132, 1.6,0.01, 2.1, 0.01

*SRT: severity of stripe rust (between 0 and 1)
FUNCTION SRT=0.,0., 0.8,0.00034, 1.6,0.002, 2.1, 0.

*PMT: severity of powdery mildew (between 0 and 1)
FUNCTION PMT=0.,0., 0.8,0.0066, 1.6,0.02, 2.1, 0.02

*FHBT: fraction of kernels with fusarium head blight symptoms
* (between 0 and 1)
FUNCTION FHBT=0.,0.02, 2.1,0.02

*Eyespot: fraction of tillers with slight, moderate, and severe
*symptoms (as defined by Scott & Hollins, 1974) are used as
*driving functions
*65, 25, 10% tillers with light, moderate, severe infection
*FTES1: fraction of tillers with light eyespot symptoms on stems
FUNCTION FTES1T=0.,0., 0.75,0., 2.,0.195, 2.1,0.195
*FTES2: fraction of tillers with moderate eyespot symptoms on stems
FUNCTION FTES2T=0.,0., 0.75,0., 2.,0.075, 2.1,0.075
*FTES3: fraction of tillers with severe eyespot symptoms on stems
FUNCTION FTES3T=0.,0., 0.75,0., 2.,0.03, 2.1,0.03

*Sharp eyespot: fraction of tillers with light, moderate, and severe
*symptoms (as defined by Clarkson & Cook, 1983) are used as
*driving functions.
*65, 25, 10% tillers with light, moderate, severe infection
*FSES1: fraction of tillers with slight sharp eyespot symptoms on stems
FUNCTION FSES1T=0.,0., 0.75,0., 2.,0.065, 2.1,0.065
*FSES2: fraction of tillers with moderate sharp eyespot symptoms on stems
```

```
FUNCTION FSES2T=0.,0., 0.75,0., 2.,0.025, 2.1,0.025
*FTSES3: fraction of tillers with severe sharp eyespot symptoms on stems
FUNCTION FSES3T=0.,0., 0.75,0., 2.,0.01, 2.1,0.01

*Brown foot rot: fraction of tillers with slight and severe
*symptoms (derived from Smiley et al., 2005) are used as
*driving functions.
*80 and 20% tillers with light, severe infection
*FBFR1: fraction of tillers with slight brown foot rot symptoms on stems
FUNCTION FBFR1T=0.,0., 0.75,0., 2.,0.16, 2.1,0.16
*FBFR2: fraction of tillers with severe brown foot rot symptoms on stems
FUNCTION FBFR2T=0.,0., 0.75,0., 2.,0.04, 2.1,0.04


*1.3 Generic function for weather
FUNCTION RADT = 1.,1.9, 15.,2.1, 46.,4.4, 74.,7.8, 105.,13., ...
135.,16.3, 166.,17.5, 196.,15.6, 227.,13.8, 258.,10., ...
288.,5.8, 319.,2.7, 349.,1.7
FUNCTION MAXT = 1.,5., 15.,4.3, 46.,5.4, 74.,8.9, 105.,12.4, ...
135.,17.3, 166.,20.5, 196.,21.4, 227.,21.5, 258.,18.9, 288.,14.3, ...
319.,8.6, 349.,5.5
FUNCTION MINT = 1.,0., 15.,-0.7, 46.,-0.6, 74.,1.2, 105.,3.3, ...
135.,7.3, 166.,10.3, 196.,12.2, 227.,12., 258.,9.7, 288.,6.5, ...
319.,2.9, 349.,0.6

*2. Weather data and timing variables
*RDD is expressed in KJ m-2 d-1 in input file
*it is then entered in the model in J m-2 d-1
*RDD is thus divided by 1 000 000 to compute RAD,
*and RAD is then expressed in MJ m-2 d-1

WEATHER WTRDIR='C:\SYS\WEATHER\', CNTR='PHIL', ISTN=1, IYEAR=1998

XRDD  =AFGEN(RADT,TIME)
XTMMX  =AFGEN(MAXT,TIME)
XTMMN  =AFGEN(MINT,TIME)

TMAX  =INSW(SWIWTH,TMMX,XTMMX)
TMIN  =INSW(SWIWTH,TMMN,XTMMN)
RAD   =INSW(SWIWTH,RDD/1000000.,XRDD)

*3. Computation of degree days above the thermal threshold

STEMP  =INTGRL(STEMPI,DTEMP)
DTEMP  =MAX(0.,((TMAX+TMIN)/2.)-TBASE)

*4. Computation of development stage

DVS   =AFGEN(DVST,STEMP)

*5. Daily accumulation of biomass, and partitionning
*in roots,leaves, stems, and ears. Mortality of leaves and stems

*5.1 Biomass accumulation
RGATT  =RAD*RUE*(1.-EXP(-K*LAI)
RG   =RAD*(RUE*(1.-EXP(-K*LAI))*...
     (RFAPH*RFBYDV*RFWEED*RFTA*RFES*RFSES*RFBFR)*...
     (MAX(0.,RFSNDV)*MAX(0.,RFSTDV)*...
     MAX(0.,RFSR)*MAX(0.,RFLR)))-RSAP
RUE   =AFGEN(RUET,DVS)
```

```
LAI    =SLA*LEAFW*((1.-STB)**BETSTB)*(1.-LR)*(1.-SNB)...
     *((1.-SR)**BETASR)*((1.-PM)**BETAPM)
SLA    =AFGEN(SLAT,DVS)

*BYDV
RFBYDV =1.-(0.35*BYDV)
BYDV   =PBYDV*AFGEN(BYDVT,DVS)

*Weeds
RFWEED =EXP(-0.003*WEED)
WEED   =PWEED*AFGEN(WEEDT,DVS)

*Take-all
RFTA   =1.-SEVTA
SEVTA  =PTA*AFGEN(SEVTAT,DVS)

*Aphids
HONEY  =INTGRL(HONI,RHONEY)
RHONEY =0.35*RSAP
RFAPH  =MAX(1.-(HONEY*0.015),0.8)
RSAP   =RRSAP*APHFW
RRSAP  =AFGEN(RRSAPT,DVS)
APHFW  =APHNB*SFWAPH
APHNB  =AFGEN(APHNBT,DVS)*PAPH
SFWAPH =AFGEN(SFWAPT,DVS)

*Septoria tritici blotch
RFSTDV =1.-(0.63*STB)
STB    =PSTB*AFGEN(STBT,DVS)

*Septoria nodorum blotch
RFSNDV =1.-(0.63*SNB)
SNB    =PSNB*AFGEN(SNBT,DVS)


*Leaf rust
*The amount of assimilates to be diverted is made a fraction over
*assimilate taken would there be no injury
*this fraction is used to compute the reduction factor
RFLR   =1.-(RUPLR/RGATT)
RUPLR  =4.62*1.0E-6*NPUSLR
NPUSLR =LR*LAI/SURFLR
SURFLR =1.0E-6
LR    =PLR*AFGEN(LRT,DVS)

*Stripe rust
RFSR   =1.-(RUPSR/RGATT)
RUPSR  =4.62*1.0E-6*NPUSSR
NPUSSR =SR*LAI/SURFSR
SURFSR =1.0E-6
SR    =PSR*AFGEN(SRT,DVS)

*Powdery mildew
PM    =PPM*AFGEN(PMT,DVS)

*Eyespot
RFES   =(1.-(0.03*ES1)-(0.28*ES2)-(0.78*ES3))
ES1    =PES*AFGEN(FTES1T,DVS)
ES2    =PES*AFGEN(FTES2T,DVS)
ES3    =PES*AFGEN(FTES3T,DVS)
```

```
*Sharp eyespot
RFSES  =(1.-(0.07*SES1)-(0.14*SES2)-(0.65*SES3))
SES1   =PSES*AFGEN(FSES1T,DVS)
SES2   =PSES*AFGEN(FSES2T,DVS)
SES3   =PSES*AFGEN(FSES3T,DVS)

*Brown foot rot
RFBFR  =(1.-(0.26*BFR1)-(0.67*BFR2))
BFR1   =PBFR*AFGEN(FBFR1T,DVS)
BFR2   =PBFR*AFGEN(FBFR2T,DVS)

*5.2 Dry weight of leaves
LEAFW  =INTGRL(LEAFWI,RLEAFW)
RLEAFW =(CPL*(1.-CPR)*RG)-RSENL
CPL   =AFGEN(CPLT,DVS)
RSENL  =RRSENL*LEAFW
RRSENL =AFGEN(RRSENT,DVS)

*5.3 Dry weight of stems
STEMW  =INTGRL(STEMWI,RSTW)
RSTW  =(CPS*(1.-CPR)*RG) -RDIST
CPS   =AFGEN(CPST,DVS)
RDIST  =INSW(DVS-1.,0.,DDIST)
MAXST  =INTGRL(MAXSTI,RMSTW)
RMSTW  =(CPS*(1.-CPR)*RG)
DDIST  =FRDIST*MAXST*RDEV2*DTEMP

*5.4 Dry weight of ears
EARW  =INTGRL(EARWI,REARW)
REARW  =(((CPE*(1.-CPR)*RG)+RDIST)*(1.-(1.1*FHB)))-(LODG*ES3*EARW)
CPE   =1.-CPL-CPS
FHB   =PFHB*AFGEN(FHBT,DVS)
LODG  =INSW(DVS-1.8,0.,0.017)

*5.5 Dry weight of roots
ROOTW  =INTGRL(ROOTWI,RROOTW)
RROOTW  =CPR*RG
CPR   =AFGEN(CPRT,DVS)

TERMINAL

YIELD=EARW*0.85

*PRINT WEED,BYDV,SEVTA,APHNB,STB,SNB,LR,SR,PM
PRINT DVS,LEAFW,ROOTW,STEMW,EARW,LAI
*PRINT DVS,DACE,CPE,CPL,CPR,CPS

PRINT YIELD
END

*run1: aphids
PARAM PAPH=1.,PBYDV=0.,PWEED=0.,PTA=0.,PSTB=0.,PLR=0.,PFHB=0.
PARAM PPM=0.,PES=0.,PSR=0.,PSNB=0.,PSES=0.,PBFR=0.
END
*run2: BYDV
PARAM PAPH=0.,PBYDV=1.,PWEED=0.,PTA=0.,PSTB=0.,PLR=0.,PFHB=0.
PARAM PPM=0.,PES=0.,PSR=0.,PSNB=0.,PSES=0.,PBFR=0.
END
*run3: WEEDS
```

```
PARAM PAPH=0.,PBYDV=0.,PWEED=1.,PTA=0.,PSTB=0.,PLR=0.,PFHB=0.
PARAM PPM=0.,PES=0.,PSR=0.,PSNB=0.,PSES=0.,PBFR=0.
END
*run4: take-all
PARAM PAPH=0.,PBYDV=0.,PWEED=0.,PTA=1.,PSTB=0.,PLR=0.,PFHB=0.
PARAM PPM=0.,PES=0.,PSR=0.,PSNB=0.,PSES=0.,PBFR=0.
END
*run5: Septoria tritici blotch
PARAM PAPH=0.,PBYDV=0.,PWEED=0.,PTA=0.,PSTB=1.,PLR=0.,PFHB=0.
PARAM PPM=0.,PES=0.,PSR=0.,PSNB=0.,PSES=0.,PBFR=0.
END
*run6: Septoria nodorum
PARAM PAPH=0.,PBYDV=0.,PWEED=0.,PTA=0.,PSTB=0.,PLR=0.,PFHB=0.
PARAM PPM=0.,PES=0.,PSR=0.,PSNB=1.,PSES=0.,PBFR=0.
END
*run7: leaf rust
PARAM PAPH=0.,PBYDV=0.,PWEED=0.,PTA=0.,PSTB=0.,PLR=1.,PFHB=0.
PARAM PPM=0.,PES=0.,PSR=0.,PSNB=0.,PSES=0.,PBFR=0.
END
*run8: stripe rust
PARAM PAPH=0.,PBYDV=0.,PWEED=0.,PTA=0.,PSTB=0.,PLR=0.,PFHB=0.
PARAM PPM=0.,PES=0.,PSR=1.,PSNB=0.,PSES=0.,PBFR=0.
END
*run9: powdery mildew
PARAM PAPH=0.,PBYDV=0.,PWEED=0.,PTA=0.,PSTB=0.,PLR=0.,PFHB=0.
PARAM PPM=1.,PES=0.,PSR=0.,PSNB=0.,PSES=0.,PBFR=0.
END
*run10: fusarium head blight
PARAM PAPH=0.,PBYDV=0.,PWEED=0.,PTA=0.,PSTB=0.,PLR=0.,PFHB=1.
PARAM PPM=0.,PES=0.,PSR=0.,PSNB=0.,PSES=0.,PBFR=0.
END
*run11: eyespot
PARAM PAPH=0.,PBYDV=0.,PWEED=0.,PTA=0.,PSTB=0.,PLR=0.,PFHB=0.
PARAM PPM=0.,PES=1.,PSR=0.,PSNB=0.,PSES=0.,PBFR=0.
END
*run12: Sharp eyespot
PARAM PAPH=0.,PBYDV=0.,PWEED=0.,PTA=0.,PSTB=0.,PLR=0.,PFHB=0.
PARAM PPM=0.,PES=0.,PSR=0.,PSNB=0.,PSES=1.,PBFR=0.
END
*run13: Fusarium root rot
PARAM PAPH=0.,PBYDV=0.,PWEED=0.,PTA=0.,PSTB=0.,PLR=0.,PFHB=0.
PARAM PPM=0.,PES=0.,PSR=0.,PSNB=0.,PSES=0.,PBFR=1.
END
*run14: all injuries combined
PARAM PAPH=1.,PBYDV=1.,PWEED=1.,PTA=1.,PSTB=1.,PLR=1.,PFHB=1.
PARAM PPM=1.,PES=1.,PSR=1.,PSNB=1.,PSES=1.,PBFR=1.
END

STOP
```

7. ANNEX 4.

Recording Form (1/3)
General information

Timing of development stage

Date of seedling emergence	
Date of flowering	
Date of grain maturity	

Additional survey for characterization of the Production Situation

Village name, location	
Type of farm, associated breeding	Ex mixte
Approximate field area (ha)	
Estimated yield (attainable yield)	
Previous crop	
Crop sequence / fallow period	
Tillage practices	
Wheat variety	
water management practices	(irrigation, drought period)
Fertilizer input	Name (NPK, other)/ quantity (kg/ha)/ date of application
Pesticide use	Name / quantity (dose and volume)/ date of application
Herbicide use	Name / quantity (kg/ha)/ date of application
Other weed control practices	

Recording Form (2/3)
Injuries assessments

Date (dd/mm/yyyy) : ____________
Plot number : ____________

A	number of plants per m² (density, D)	
B	Dry biomass of weeds (g/0.25m²)	
	BYDV: Percentage of plants with Barley Yellow Dwarf Viruses symptoms (%)	

		Pl.1	Pl.2	Pl.3	Pl.4	Pl.5
C	Number of aphids					
D	Percentage of roots length with Take-all symptoms (%)					
E	Percentage of tillers with slight Eyespot symptoms (%)					
F	Percentage of tillers with moderate Eyespot symptoms (%)					
G	Percentage of tillers with severe Eyespot symptoms (%)					
H	Percentage of tillers with slight Sharp Eyespot symptoms (%)					
I	Percentage of tillers with moderate Sharp Eyespot symptoms (%)					
J	Percentage of tillers with severe Sharp Eyespot symptoms (%)					
K	Percentage of tillers with slight Fusarium Stem Rot symptoms (%)					
L	Percentage of tillers with severe Fusarium Stem Rot symptoms (%)					
M	Percentage of kernels disease by Fusarium Head Blight (%)					
N	Septoria tritici blotch severity (percentage of leaf surface affected) (%)					
O	Septoria nodorum blotch severity (percentage of leaf surface affected) (%)					
P	Brown rust severity (percentage of leaf surface affected) (%)					
Q	Yellow rust severity (percentage of leaf surface affected) (%)					
R	Powdery Mildew severity (percentage of leaf surface affected) (%)					

Pl = plant.
The following injury variable are then computed by :
WD=B/0.25; APH =(moyC)*A; TAK=(moyD); EYS1=moyE; EYS2=moyF; EYS3=moyG; SHY1=moyH; SHY2=moyI; SHY3=moyJ; FST1=moyK; FST2=moyL; FHB=moyM; ST=moyN; SN=moyO; BR=moyP; YR=moyQ; PM=moyR.

Recording Form (3/3)
Crop growth assessments

Date (dd/mm/yyyy) :
Plot number :

A	number of plants per m² (density, D)	
B	Number of plant sampled	
C	Dry biomass of roots of sampled plants	
D	Dry biomass of living leaves of sampled plants	
E	Dry biomass of dead leaves of sampled plants	
F	Dry biomass of stems of sampled plants	
G	Dry biomass of ears of sampled plants	
H	Dry biomass of field grain of sampled plants (at final harvest)	
I	Total living leaf area of sampled plants	

ROOTBM=C/B*A; LEAFBM=D/B*A; SENLBM=E/B*A; STEMBM=F/B*A; EARBM=G/B*A; YIELD=H/B*A; SLA=I/D; LAI=I/B*A

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