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# Adaptation of the CROPGRO model to simulate growth and yield of rapeseed (*Brassica napus* L. var. *oleifera* D.C.)

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## ABSTRACT

In Mediterranean area where its cycle lasts nearly seven months, the growth of winter oilseed rape *Brassica napus* L. is subjected to climatic hazards that may exert an important influence on yield, notwithstanding damage by pests. In the context of the European Common Agricultural Policy, which promoted in Europe the growing of rape as a bio–fuel crop, it seemed relevant to study the effects of soil and climate variability on both the final yield and the environmental impacts of this crop. As a consequence of their dynamic nature, these effects may only be studied by means of a model simulating the relevant crop processes as related to management and weather conditions.

Here we tried to adapt the CROPGRO Soybean module to rapeseed by modifying species and cultivar file parameters for net canopy photosynthesis, N uptake, partitioning of C and N assimilates between crop compartments roots, leaves, stems, pods, grain etc. The resulting model, is described and tested against experimental data in this thesis. All the parameters mentioned have been calibrated on a data set from a one–year experiment conducted on the experimental farm of the University of Sassari (Northwestern Sardinia) and on a private farm, located in the Central Sardinia. In both sites, cv Kabel was studied. Weather data were recorded with automatic weather stations, while phenological stages were weekly monitored. In order to analyze the crop growth, destructive measurements were carried out every four weeks. Specific crop parameters including specific leaf area, the leaf stem partitioning parameter, and photothermal time requirements for crop development were generated from field sampling.

The modified soybean version of CROPGRO performs realistically but should be tested under different latitude.

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# 1. OBJECTIVES

Concern over climate change is raising awareness on the need to use clean energy. The EU biofuels directive (European Parliament and the Council, 2003) promotes the use of biofuels in order to help Europe meet its greenhouse gas (GHG) emission reduction commitments, improve its security sources so that it reduces its dependence on oil imports and makes greater use of indigenous resources. The directive sets a European target of 2% substitution of conventional transport fuels by biofuels by December 2005 and a further 5.75% substitution by December 2010. Moreover, the European Commission, is committed to encourage the production and use of biofuels by proposing to set a binding minimum target for renewable energy sources of 10% of final energy use in the transport sector by 2020 (Commission of the European Communities, 2007; Council of the European Union, 2008), and is also working on changing fuel specifications to allow higher than 5% blends of biofuel (Commission of the European Communities, 2008). Following the implementation of policies aimed at increasing the production of locally produced bio–fuels, the growing of rapeseed as oilseed crop for energy production in Southern Europe has gained new interest.

The global area of rapeseed has increased from just over 7 million ha in 1965 to almost 30 million ha in 2007. This increase represents a doubling of the area grown every 20 years. In 2007, Europe grew the greatest proportion of the world's rapeseed area (0.27), followed by China (0.23), India (0.22), Canada (0.19) and Australia (0.04) (www.faostat.fao.org). Since 1995, the greatest proportional increases in area grown have taken place in Australia and Europe (Berry and Spink, 2006).

Oilseed rape is the third most important source of vegetable oil in the world behind palm oil (0.32) and soybean (0.29) (www.faostat.fao.org). Oilseed rape also provides about 0.12 of the world supply of protein meal (www.usda.gov). It is also an excellent rotation crop to control cereal diseases, pests and weeds. It has a good stable yield, which requires normal farm equipment. It grows in areas that receive more than 300 mm of rain, well–drained soil with a good potential for growing wheat, relatively free of broad leaf weeds, and residues of broad leaf herbicides. However, care needs to be taken not to plant in areas where it has grown consecutively for the last three seasons (Grombacher and Nelson, 1996).

Agricultural research is relatively expensive because of the multiple factors that affect yield and quality, and the crop's relatively long cycle. The heterogeneity of climatic and edaphic conditions existing in the Mediterranean area requires a high number of specific trials, thus notably increasing both, the time taken to make decisions on, and the costs of technology transfer.

The development of analytical models on production systems has considerably reduced both time and costs. The models use equations constructed on the basis of biophysical theory and experimental results and are likewise validated through experimental trials. Once validated, the models permit experimentation and provide support for planning decisions in research, technology transfer, and agricultural development. Furthermore, the models help predict scenarios for land use, explore opportunities for potential, but distinct alternatives, identify policies of intervention, and develop support systems for decision making in research and technology transfer (Bouma, 1998). A major characteristic of support systems, for decision making in agrotechnology, is their orientation toward meeting the demand for solutions to specific production problems (Stoorvogel, 1998). One practical value of simulation models is its utility in situations where carrying out research is physically or economically difficult (Aguilar and Cañasm, 1992; Quiroz *et al*., 1996). Models help to quickly find answers to such questions as "What would happen to a crop's yield and quality if more fertilizer were applied, or if climate or soil changed?" (Bouma, 1998). Models do not make decisions, but help technicians and farmers towards making the right decisions (Stoorvogel, 1998). In other words a process model might offer the potential for integrating the physiological understanding of rapeseed and examining how potential growth and major limitations to production might vary in different environments and with different management scenarios. This information should lead to more efficient experimentation and targeting of rapeseed. Therefore, the CROPGRO model for legumes was used as a framework for reviewing the physiology of rapeseed and converting this information into quantitative predictions, rather than developing a new crop model. This model was chosen because it has performed well with similar crop and is widely used in the international agricultural research community (IBSNAT, 1993; Tsuji, 1998; Uehara and Tsuji, 1998). The CROPGRO model has been implemented within the Decision Support System for Agrotechnology

Transfer–DSSAT (Tsuji *et al*., 1994) to provide a user friendly interface. DSSAT crop models can be linked to analyze rotation systems (Thornton *et al.*, 1997), as described in studies by Timsina *et al*. (1997) and Singh *et al*. (1999a, 1999b).

The objective of this study, supported by the Ministry of Agricultural, Food and Forestry Policies (Bioenergie Project), Sardinia Region (Biomasse Project) and by a private company (Ottana Energia–BioPower Sardegna) was to adapt the generic legume model CROPGRO (Hoogenboom *et al.*, 1992; Boote *et al.*, 1998a, 1998b) to simulate growth and development of oilseed rape cv. Kabel (*Brassica napus* L. var. *oleifera* D.C.) as a function of soil, weather and management conditions. The CROPGRO model simulates different grain legume species using external parameter files that describe species process sensitivity to environment plus files describing cultivar differences. Specific objectives were to develop a species file and one cultivar file for rapeseed based on: (i) values and relationships from the literature and (ii) comparison with observed growth data on rapeseed grown in Sardinia. As consequence, this dissertation reviews the physiology of oilseed rape and describes the methodological process and results of determining the specific parameters so as to simulate the criteria for dry matter production and seed yield by calibrating the CROPGRO model.

# 2. LITERATURE REVIEW

## *2.1 Models*

Crop systems are complex in nature. This complexity makes the use of growth models significant in simulating the real system. There are different types of mathematical models used in crop production. Addiscott and Wagnet (1985) classified models as deterministic or stochastic, mechanistic or functional and rate or capacity type. They explained deterministic models as models that generate a specific result for a specific set of events and are related to a certain degree of uncertainty. However, stochastic models accommodate spatial variability and quantify the degree of uncertainty caused due to spatial variability of the mediating processes. Stochastic models generate an uncertain result for they encompass one or more random variables with a related probability distribution. Ritchie and Johnson (1990) classified deterministic models into mechanistic or functional. Mechanistic models are based on dynamic rate concepts and basic processes. Functional models are based on capacity factors, and deal with processes in a simplified way. The main difference between functional and mechanistic models is on their role either as research or management tools. Mechanistic models are mainly used as research tools because they are very helpful in understanding the integrated systems of nature. However, functional models require less input and this makes them handy to be used for management purposes. They are broadly used and are validated independently.

Models can also be classified based on the factors they include. Penning De Vries, Jansen, Ten Berge and Bakema (1989) classified crop growth models into four levels based on the factors they include. Level one crop growth models, respond only to weather variables, mainly temperature and solar radiation and they simulate potential yield of a crop without water stress, lack of nutrients and without other constraints. Level two crop growth models include a soil water balance and the influence of soil water deficit on the growth of the crop and yield. Level three crop growth models include the availability of nitrogen in the soil and the effect of adding nitrogen fertilizer on the growth and yield of crops. In addition, they include the interaction between nitrogen, water and weather factors. Level four models include the remaining stress factors like pests and nutrients other than nitrogen.

### 2.1.2 DSSAT (Decision Support System for Agrotechnology Transfer)

The decision support system for agrotechnology transfer (DSSAT) was originally developed by an international network of scientists, cooperating in the International Benchmark Sites Network for Agrotechnology Transfer project, to facilitate the application of crop models in a systems approach to agronomic research. Its initial development was motivated by a need to integrate knowledge about soil, climate, crops, and management for making better decisions about transferring production technology from one location to others where soils and climate differed. The systems approach provided a framework in which research is conducted to understand how the system and its components function. This understanding is then integrated into models that allow one to predict the behavior of the system for given conditions. After one is confident that the models simulate the real world adequately, computer experiments can be performed hundreds or even thousands of times for given environments to determine how to best manage or control the system. DSSAT was developed to operationalize this approach and make it available for global applications (Jones *et al.*, 2003).

The Decision Support System for Agrotechnology Transfer (DSSAT) comprises six models for simulating the growth of 16 crops of economic importance. It has demonstrated high reliability under different climates, soil, and management conditions (Jones, 1993). With this modeling system, it is possible to:

- Organize and file databases on climate, soils, crops, experiments, and prices;
- Simulate crop production in one or various periods and in sequences;
- Analyze results and graphically present simulations; and
- Evaluate different management practices, specific to one farm or its part (Jones, 1993).

The DSSAT Cropping System Model (CSM) simulates growth and development of a crop over time, as well as the soil water, carbon and nitrogen processes and management practices. Figure 2.1 shows the main components of CSM. These include:

- A main driver program, which controls timing for each simulation;
- A Land unit module, which manages all simulation processes which affect a unit of land;

- Primary modules that individually simulate the various processes that affect the land unit including weather, plant growth, soil processes, soil–plant–atmosphere interface and management practices.

Collectively, these components simulate the changes over time in the soil and plants that occur on a single land unit in response to weather and management practices. Unlike previous versions of DSSAT and its crop models, the DSSAT–CSM incorporates models of all crops within a single set of code. This design feature greatly simplifies the simulation of crop rotations since soil processes operate continuously, and different crops are planted, managed, and harvested according to cropping system information provided as inputs to the model. DSSAT–CSM was restructured from previous DSSAT crop models into a modular format, which is described by Jones *et al.* (2001) and Porter *et al.* (2000). The most important features of this approach are:

- Modules separate along disciplinary lines.
- Clear and simple interfaces are defined for each module.
- Individual modular components can be plugged in or unplugged with little impact on the main program or other modules, i.e., for comparison of different models or model components.
- The modular format facilitates documentation and maintenance of code.
- Modules can be written in different programming languages and linked together.
- Modules can be easily integrated into different types of application packages due to the well–defined and documented interfaces.
- The modular format allows for to possibility of integrating other components, such as livestock and intercropping, through well–defined module interfaces.

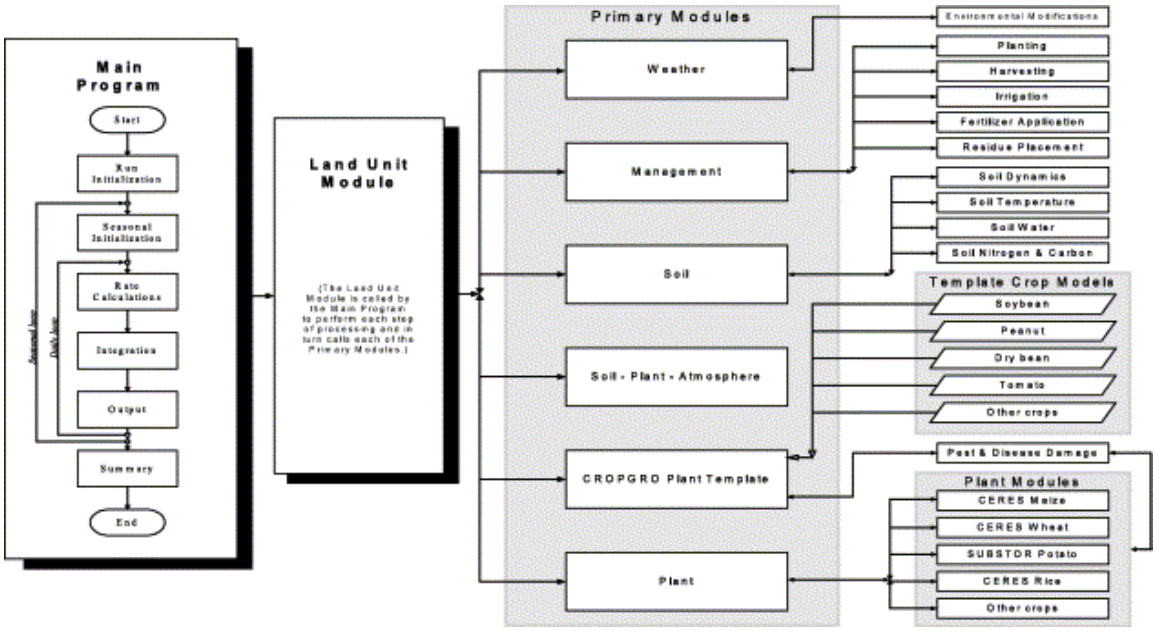



**Figure 2.1** Overview of the components and modular structure of DSSAT–CSM.

Cooperation among different model development groups is facilitated. Each group focus on specific modules as building blocks for expanding the scope and utility of the cropping system model. As shown in Figure 2.1, each module has six operational steps, (run initialization, season initialization, rate calculations, integration, daily output, and summary output). The main program controls the timing of events: the start and stop of simulation, beginning and end of crop season, as well as daily time loops. This feature, an adaptation of Van Kraalingen's (1991, 1995) work, allows each module to read its own inputs, initialize itself, compute rates, integrate its own state variables, and write outputs completely independently from the operation of other modules. Sub modules operate exactly like primary modules in that each will usually perform two or more of the six steps (run initialization, seasonal initialization, rate calculations, integration, daily output and seasonal summary). There can be additional levels of sub modules, each behaving the same way. For example, the CERES–Maize sub module could have a phenology sub module. One could unplug this phenology module, and introduce a new one, if desired, without changing the rest of the CERES–Maize module. Any module or sub module can also have other subroutines as needed; there are no technical restrictions about how simple or complex a module should be. There are two ways of interfacing crop growth routines in the DSSAT–CSM. A new plant growth routine can be introduced by interfacing it with the Plant module. This is the approach that was used to introduce the CERES–Maize, –Millet, –Sorghum, and –Rice models into DSSAT–

CSM. These routines operated as stand–alone crop models in DSSAT v3.5. The second way to introduce a new crop is through the use of a crop template approach. This can be implemented through the CROPGRO module and allows users to modify values in a species crop template file without changing any code. The CROPGRO development team has used this approach in creating models for different species, including faba bean (Boote *et al.*, 2002), brachiaria grass (Giraldo *et al.*, 1998), tomato (Scholberg *et al.*, 1997), chickpea (Singh and Virmani, 1996) and velvet bean (Hartkamp *et al.*, 2002), for example. A major advantage of this approach is that working with the crop template is less prone to errors as no changes to the model code are required. The major disadvantage to this method is that crops with very different life cycles from that described by the CROPGRO approach may not be adequately modeled.

### 2.1.3 Component descriptions

The main program reads information from the DSSAT standard file that describes a particular experiment or situation to be simulated (Hunt *et al.*, 2001) and sets a number of variables for controlling a simulation run. It initiates the simulation by setting the DYNAMIC variable for initializing the run and calls the Land Unit module. It then starts a crop season time loop and calls the Land Unit module for initializing variables that must be set at the start of each season.

After initialization of the seasonal loop, the main program starts a daily loop and calls the Land Unit module three times in sequence, first to compute rates, secondly to integrate, and finally to report daily outputs. After a crop season is completed, it calls the Land Unit module to produce season–end variables and to create summary output files. The main program provides these timing and simulation control variables to all modules. The Land Unit module calls each of the primary cropping system modules. At the start of each new crop season, it obtains management information from the DSSAT input file. The Land Unit and Primary modules link to sub modules, and thus are used to aggregate processes and information describing successive components of the cropping system. Table 2.2 shows the variables that are currently passed from each of the Primary modules to the Land Unit module, excluding the timing and control variables. These interface

variables are available for any primary module since they are passed into the Land Unit module (Jones *et al*., 2003).

**Table 2.2** Summary description of modules in the DSSAT–CSM.

| Modules | Sub modules | Behavior |
|---|---|---|
| Main program (DSSAT–CSM) | | Controls time loops, determines which modules to call based on user input switches, controls print timing for all modules. |
| Land Unit | | Provides a single interface between cropping system behavior and applications that control the use of the cropping system. It serves as a collection point for all components that interact on a homogenous area of land. |
| Weather | | Reads or generates daily weather parameters used by the model. Adjusts daily values if required, and computes hourly values |
| Soil | Soil dynamics | Computes soil structure characteristics by layer. This module currently reads values from a file. |
| | Soil weather module | Computes soil temperature by layer. |
| | Soil water module | Computes soil water processes including snow accumulation and melt, runoff, infiltration, saturated flow and water table depth. Volumetric soil water content is updated daily for all soil layers. |
| | Soil nitrogen and carbon module | Computes soil nitrogen and carbon processes, including organic and inorganic fertilizer and residue placement, decomposition rates, nutrient fluxes between various pools and soil layers. Soil nitrate and ammonium concentrations are updated on a daily basis for each layer. |
| SPAM | | Resolves competition for resources in soil–plant–atmosphere system. Computes partitioning of energy and resolves energy balance processes for soil evaporation, transpiration, and root water extraction. |
| CROPGRO Crop Template module | | Computes crop growth processes including phenology, photosynthesis, plant nitrogen and carbon demand, growth partitioning, and pest and disease damage for crops modeled using the CROPGRO model Crop Template. |
| Individual plant growth modules | CERES–Maize, CERES–Wheat, CERES–Rice, Substor–Potato, other plant models | Modules that simulate growth and yield for individual species. Each is a separate module that simulates phenology, daily growth and partitioning, plant nitrogen and carbon demands etc. |
| Management operations module | Planting | Determines planting date based on read–in value or simulated using an input planting window and soil, weather conditions. |
| | Harvesting | Determines harvest date, based on maturity, read–in value or on a harvesting window along with soil, weather conditions. |
| | Irrigation | Determines daily irrigation, based on read–in values or automatic applications based on soil water depletion. |
| | Fertilizer | Determines fertilizer additions, based on read–in values or automatic conditions. |
| | Residue | Application of residues and other organic material as read–in values or simulated in crop rotations. |

*Weather module*

The main function of the weather module is to read or generate daily weather data. It reads in daily weather values (maximum and minimum air temperatures, solar radiation and precipitation, relative humidity and wind speed when available), from the daily weather file. Hourly weather values are computed for use by some modules that require them. This module generates daily weather data using the WGEN (Richardson, 1981, 1985) or SIMMETEO (Geng *et al.*, 1986, 1988) weather generators. It also can modify daily weather variables for studying climate change or simulating experiments in which solar radiation, rainfall, maximum and minimum

temperatures, day length, and/or atmospheric $CO_2$ concentrations were set at constant values or increased/decreased relative to their read–in values. Based on the inputs provided from the experiment file, the Weather module knows whether to just read in daily values or to generate or modify them (using the Environmental Modification sub module).

*Soil module*

The soil in the land unit is represented as a one–dimensional profile; it is homogenous horizontally and consists of a number of vertical soil layers. The Soil module integrates information from three sub modules: soil water, soil carbon and nitrogen, and soil dynamics. The soil dynamics module is designed to read in soil parameters for the land unit and to modify them based on tillage, long–term changes in soil carbon, or other field operations. Currently, the module reads in soil properties from a file, checks them for validity and makes these soil properties available to other modules.

*Soil–plant–atmosphere module*

This module computes daily soil evaporation and plant transpiration. The current version was originally developed by Ritchie (1972) and was used in all of the DSSAT v3.5 crop models as part of the soil water balance. This module brings together soil, plant and atmosphere inputs and computes light interception by the canopy, potential evapotranspiration (ET) as well as actual soil evaporation and plant transpiration. It also computes the root water uptake of each soil layer. The daily weather values as well as all soil properties and current soil water content, by layer, are required as input. In addition, leaf area index (LAI) and root length density for each layer are needed. The module first computes daily net solar radiation, taking into account the combined soil and plant canopy albedo. It calculates potential ET using one of two current options. The default Priestley and Taylor (1972) method requires only daily solar radiation and temperature, and was described in detail by Ritchie (1972), Ritchie and Otter, (1985) and Jones and Ritchie (1991). The Penman–FAO (Doorenbos and Pruitt, 1977) method for computing potential ET can optionally be used to better account for arid or windy conditions, but weather data files must include wind and humidity data. The potential ET is partitioned into potential soil evaporation based on the fraction of solar energy reaching the soil

surface, based on a negative exponential function of LAI, and potential plant transpiration. Actual soil evaporation is based on a two–stage process (Ritchie, 1972). After the soil surface is first wetted due to either rainfall or irrigation, evaporation occurs at the potential rate until a cumulative soil evaporation amount since wetting is reached. Then, a soil–limiting daily soil evaporation amount is computed as a square root function of time since stage one ended. Actual soil evaporation is the minimum of the potential and soil–limiting calculations on a daily basis. If evaporation is less than potential soil evaporation, this difference is added back to potential plant transpiration to account for the increased heat load on the canopy when the soil surface is dry (Ritchie, 1972). To determine whether the soil or atmosphere limits plant transpiration, potential root water uptake is computed by calculating a maximum water flow to roots in each layer and summing these values (Ritchie and Otter, 1985; Ritchie, 1998; Jones and Ritchie, 1991). These calculations account for root length density in each layer and the soil water content in the layer. The equation that computes potential root water uptake in each layer is an approximation to the radial flow equation, where assumptions are made about soil texture effect on hydraulic conductivity, root diameter, and a maximum water potential difference between roots and the soil. The actual plant transpiration is then computed as the minimum of potential plant transpiration and the potential root water uptake. Thus, the atmosphere can limit transpiration by low solar radiation and cool temperatures, the canopy can limit it by low LAI, and the soil can limit it by low soil water content, low root length density, and their distributions relative to each other. This method for computing ET has provided an excellent functional approach for determining water stress in the plant without explicitly modeling water status in the plant component. The ratio of actual ET to potential ET, if less than 1.0, indicates that stomatal conductance would have had to be decreased sometimes during the day to prevent plant desiccation. This ratio is typically used in the Plant modules to reduce photosynthesis in proportion to relative decreases in transpiration. Similarly, a ratio of potential root water uptake and potential transpiration is used to reduce plant turgor and expansive growth of crops. The rationale for this is that as soil water becomes more limiting, turgor pressure in leaves would decrease and affect leaf expansion before photosynthesis is reduced. In the current Plant modules this ratio is set to 1.5.

*CROPGRO template module*

CROPGRO is a mechanistic, process–oriented model for grain legumes that includes crop development, C balance, crop and soil N balance, and soil water balance subroutines (Boote *et al.*, 1998a, 1998b). Crop development includes processes such as vegetative and reproductive development, which determine life cycle duration, duration of root and leaf growth, onset and duration of reproductive organs such as pods and seeds, and thereby influence dry matter partitioning to plant organs over time. Crop C balance includes daily inputs from photosynthesis, conversion and condensation of C into crop tissues, C losses to abscised parts, and growth and maintenance respiration. The C balance also simulates leaf area expansion, growth of vegetative tissues, pod addition, seed addition, shell growth, seed growth, nodule growth, senescence, and carbohydrate mobilization. The crop N balance includes daily soil N uptake, $N_2$ fixation, mobilization from vegetative tissues, rate of N use for new tissue growth, and rate of N loss in abscised parts. Soil N balance processes are similar to those described by Godwin and Jones (1991). Soil water balance processes include infiltration of rainfall and irrigation, runoff, soil evaporation, distribution of root water uptake, drainage of water below the root zone, and crop transpiration (Ritchie, 1998). The time step in CROPGRO is mostly daily (corresponding to daily recording of weather information) but is hourly for some processes, such as the leaf–level hedgerow photosynthesis. Model state variables are predicted and output on a daily basis for crop, soil water, and soil N balance processes. The CROPGRO model is a generic model that uses one common FORTRAN code to predict the growth of a number of different grain legumes soybean (*Glycine max* (L.) Merr.), peanut (*Arachis hypogaea* L.), and dry bean (*Phaseolus vulgaris* L.) as well as other crops such as tomato (*Lycopersicon esculentum* Mill.) (Scholberg *et al.*, 1997; Boote *et al.*, 1998a, 1998b).

This versatility is achieved through input files that define species traits and cultivar attributes. Having one common generic code allows code improvements in the basic model, e.g., for soil water balance, soil organic matter–N balance, or soil temperature to be directly available for all of the crops. The approach has helped minimize *hard–wired* coefficients in the code for aspects that characterize individual species.

**Table 2.3** Summary of types of parameters used in the crop template approach.

| Section | Description |
|---|---|
| Photosynthesis | Canopy assimilation coefficients for effects of solar radiation and $CO_2$.<br>Light extinction coefficient.<br>Functions that define leaf N and temperature effects on photosynthesis. |
| Respiration | Respiration parameters associated with various growth processes. |
| Plant composition values | "Maximum", "normal growth", and "final" protein concentrations of leaf, stem, root, shell, seed, and nodule tissues.<br>Carbohydrate–cellulose, lipid, lignin, organic acid concentration of leaf, stem, root, shell, seed, and nodule tissues.<br>Effects of temperature on seed lipid concentration. |
| Carbon and nitrogen mining parameters | Coefficients for carbohydrate reserves in stem tissue.<br>Fraction of new leaf, stem, root and shell tissue growth that is available carbohydrate.<br>Mobilization rates of carbohydrate and protein from vegetative tissue. |
| Plant growth and partitioning parameters | Dry matter partitioning to leaf, stem, and root as function of vegetative stage.<br>Coefficients for partitioning at emergence, final growth stage, stem senescence, during water stress, and nodule growth.<br>Parameters that define leaf expansion response to temperature and solar radiation.<br>Initial root depth and length, root water uptake parameters.<br>Relative effects of temperature on pod set, seed growth and relative change in partitioning.<br>Relative effects of soil water content on peanut pegging and pod addition. |
| Senescence factors | Senescence parameters related to vegetative stage, freeze damage, nitrogen mobilization, drought, canopy self shading. |
| Phenology parameters | Curves that define temperature effect on vegetative, early reproductive, and late reproductive development.<br>Parameters for each growth stage: preceding stage, photoperiod function, temperature function, temperature and water sensitivity, N & P sensitivity. |
| Canopy height and width parameters | Internode length and canopy width increase as a function of plant vegetative stage.<br>Internode elongation as a function of temperature and photosynthetic photon flux density. |

This generic–model approach with its read–in species and cultivar traits has helped model developer in modifying CROPGRO for other species, such as cowpea (*Vigna unguiculata* L.) (Boote, unpublished, 1998), chickpea (*Cicer arietinum* L.) (Singh and Virmani, 1996), and non legumes such as tomato (Scholberg *et al.*, 1997), cabbage, bell pepper, cotton and two grasses: bahia and brachiaria. For each given

species, the CROPGRO species file contains knowledge about base temperatures (Tb) and optimum temperatures (Topt) for developmental processes rate of emergence, rate of leaf appearance, and rate of progress toward flowering and maturity and growth processes (photosynthesis, nodule growth, $N_2$ fixation, leaf expansion, pod addition, seed growth, and N mobilization, etc.). Either short or long daylength effects on development during specific life cycle phases are allowed by the species file, with two parameters in the cultivar file indicating each cultivar's critical short (or long) daylength and the slope of daylength sensitivity that slows development at increasingly longer (or shorter) days. The species file also includes coefficients and other relationships for photosynthesis, $N_2$ fixation, tissue composition, and growth and maintenance respiration. Cultivar differences are created by 15 "cultivar" traits. The cultivar traits include two daylength sensitivity traits, five important life cycle "phase" durations, light–saturated leaf photosynthesis, vegetative traits, and reproductive traits. There are 19 traits in the ecotype file that were proposed to vary less often, such as thermal time to emergence and first leaf stages, but some traits from this file have been used frequently to characterize cultivars. Phenology is an important component of the CROPGRO crop template approach. This component uses information from the species file, which contains cardinal temperature values, as well as information from the cultivar and ecotype files, which contain physiological day durations for respective life cycle phases. Life cycle progress through any given phase depends on a physiological day accumulator as a function of temperature and day length, in many cases.

Crops like soybean are sensitive to day length, whereas other crops such as peanut are not. When the physiological day accumulator reaches a value defined by a threshold given in the cultivar file, a new growth stage is triggered. A physiological day can be thought of as equivalent to one calendar day if temperatures are optimum 24 hours per day and day length is below the critical short or long day length requirement, depending on species sensitivity.

The species file also contains coefficients that indicate the effect of water or nitrogen deficit on rate of life cycle progress. These coefficients may vary with life cycle phase; for example, water deficit may slow the onset of reproductive growth but accelerate reproductive growth after beginning seed fill.

**Table 2.4** Genetic coefficients used in the CROPGRO crop template module for modelling different crops.

| Trait | Definition of Trait |
|---|---|
| ECO# | Code for the ecotype to which this cultivar belongs. |
| CSDL | Critical Short Day Length below which reproductive development progresses with no daylength effect (for short day plants) (h). |
| PPSEN | Slope of the relative response of development to photoperiod with time (positive for short day plants) (1 $h^{-1}$). |
| EM–FL | Time between plant emergence and flower appearance (R1) (photothermal days). |
| FL–SH | Time between first flower and first pod (R3) (photothermal days). |
| FL–SD | Time between first flower and first seed (R5) (photothermal days). |
| SD–PM | Time between first seed (R5) and physiological maturity (R7) (photothermal days). |
| FL–LF | Time between first flower (R1) and end of leaf expansion (photothermal days). |
| LFMAX | Maximum leaf photosynthesis rate at 30 $^{o}$C, 350 ppm $CO_2$, and high light (mg $CO_2$ ($m^2$ $s)^{-1}$. |
| SLAVR | Specific leaf area of cultivar under standard growth conditions ($cm^2$ $g^{-1}$). |
| SIZELF | Maximum size of full leaf ($cm^2$). |
| XFRT | Maximum fraction of daily growth that is partitioned to seed + shell. |
| WTPSD | Maximum weight per seed (g). |
| SFDUR | Seed filling duration for pod cohort at standard growth conditions (photothermal days). |
| SDPDV | Average seed per pod under standard growing conditions (# [seed] $pod^{-1}$). |
| PODUR | Time required for cultivar to reach final pod load under optimal conditions (photothermal days). |
| | *Frequently used important traits from the Ecotype file* |
| R1PRO | Increase in daylength sensitivity after anthesis (CSDL decreases by this amount (h)). |
| FL–VS | Time from first flower to last leaf on main stem (photothermal days). |
| THRESH | The maximum ratio of (seed (seed+shell)$^{-1}$) at maturity. Causes seed to stop growing as their dry weight increases until shells are filled in a cohort. |
| SDPRO | Fraction protein in seeds (g [protein] g $[seed]^{-1}$). |
| SDLIP | Fraction oil in seeds (g [oil] g $[seed]^{-1}$). |

The species file also allows different cardinal temperatures for pre–anthesis development compared to post–anthesis reproductive development. The CROPGRO plant growth model allows crop photosynthesis to be calculated by two options:

- Daily canopy photosynthesis, similar to radiation use efficiency models, or
- Hourly hedgerow light interception and leaf–level photosynthesis.

The daily canopy photosynthesis option, modified from the method used in SOYGRO V5.4 (Jones *et al.*, 1989), predicts daily gross photosynthesis as a function of daily irradiance for a full canopy, which is then multiplied by factors 0 to 1 for light interception, temperature, leaf nitrogen status, and water deficit. There are additional adjustments for $CO_2$ concentration, specific leaf weight, row spacing, and cultivar.

Growth of new tissues depends on daily available carbohydrate, partitioning to different tissues, and respiration costs of tissue synthesis. During vegetative growth, the model follows a partitioning pattern dependent on vegetative growth stage, but modified by water deficit and nitrogen deficiency. Partitioning coefficients for leaf, stem, and root are defined in the species crop template file. Beginning at flowering, cohorts of flowers, pods, and seeds are added daily. These cohorts have an explicit assimilate demand per day depending on genetic potential and temperature. Reproductive tissues have first priority for assimilate over vegetative tissues, up to a maximum reproductive partitioning factor. This factor may be less than 1.0 for indeterminate plants (such as peanut and tomato) and 1.0 for determinate plants, indicating that reproductive tissue eventually can utilize 100% of the assimilate. Leaf area expansion depends on leaf weight growth and specific leaf area, where the latter depends on temperature, light, and water deficit. Leaf expansion during reproductive growth is terminated by decrease of assimilate allocated to leaf growth and by reaching a phase that terminates leaf expansion. During seed fill, nitrogen is mobilized from vegetative tissues. As a result photosynthesis declines and leaf abscission increases. Protein and carbohydrate mobilized from vegetative tissue contribute to seed growth while photosynthesis declines. Growth respiration and conversion efficiency follow the approach of Penning De Vries and Van Laar (1982) where the glucose cost for respiration and for condensation are computed as a function of the composition of each tissue. The species file contains the glucose cost to synthesize protein, lipid, lignin, organic acid, cellulose–carbohydrate, and mineral fractions as well as the approximate composition of each tissue. Maintenance respiration depends on temperature as well as gross photosynthesis and total crop mass minus protein and oil in the seed. Maintenance respiration is subtracted from

gross daily photosynthesis to give available carbohydrates for new tissue growth. Various authors have published details on these relationships and sources of data used in their development (Wilkerson *et al.*, 1983; Boote *et al.*, 1986; Jones *et al.*, 1989; Boote and Pickering, 1994; Boote *et al.*, 1997; Boote *et al.*, 1998a, 1998b; Boote *et al.*, 2002).

*Individual crop module interface (plant module)*

The individual crop module interface serves the same function as the CROPGRO Crop Template module in that it has the same interface variables, linking plant growth dynamics to the other modules in the DSSAT–CSM. However, it is designed to link modules that describe growth, development and yield for individual crops. This module links in, for example, the CERES models from DSSAT v3.5 after modifications were made to fit the modular structure. Developers have implemented several of the individual models from DSSAT v3.5 (maize, wheat, sorghum, millet, barley, and rice) as well as potato and they are converting others (Jones *et al.*, 2003). The CERES–Maize, –Wheat and –Barley models were modified for integration into the modular DSSAT–CSM. For these CERES models, the plant life cycle is divided into several phases, which are similar among the crops. Rate of development is governed by thermal time, or growing degree–days (GDD), which is computed based on the daily maximum and minimum temperatures. The GDD required to progress from one growth stage to another are either defined as a user input, or are computed internally based on user inputs and assumptions about duration of intermediate stages. Cultivar–specific inputs for all DSSAT–CSM CERES models are presented in absolute terms for consistency, a convention change from that followed previously for wheat and barley for which relative values were used. The number of GDD occurring on a calendar day is a function of a triangular or trapezoidal function defined by a base temperature, one or two optimum temperatures, and a maximum temperature above which development does not occur. Daylength may affect the total number of leaves formed by altering the duration of the floral induction phase, and thus, floral initiation. Daylength sensitivity is a cultivar specific user input. Currently, only temperature and, in some cases, daylength, drive the accumulation of GDD; drought and nutrient stresses currently have no effect. During the vegetative phase, emergence of new leaves is used to limit leaf area development until after a species–dependent number of leaves have appeared. Thereafter, vegetative branching

can occur, and leaf area development depends on the availability of assimilates and specific leaf area. Leaf area expansion is modified by daily temperature GDD, and water and nitrogen stress. Daily plant growth is computed by converting daily intercepted photosynthetically active radiation into plant dry matter using a crop–specific radiation use efficiency parameter. Light interception is computed as a function of LAI, plant population, and row spacing. The amount of new dry matter available for growth each day may also be modified by the most limiting of water or nitrogen stress, and temperature, and is sensitive to atmospheric $CO_2$ concentration. Above ground biomass has priority for carbohydrate, and at the end of each day, carbohydrate not used for above ground biomass is allocated to roots. Roots must receive, however, a specified stage–dependent minimum of the daily carbohydrate available for growth. Leaf area is converted into new leaf weight using empirical functions. Kernel numbers per plant are computed during flowering based on the cultivar's genetic potential, canopy weight, average rate of carbohydrate accumulation during flowering, and temperature, water and nitrogen stresses. Potential kernel number is a user–defined input for specific cultivars. Once the beginning of grain fill is reached, the model computes daily grain growth rate based on a user–specified cultivar input defined as the potential kernel growth rate (mg (kernel d)$^{-1}$). Daily growth rate is modified by temperature and assimilate availability. If the daily pool of carbon is insufficient to allow growth at the potential rate, a fraction of carbon can be remobilized from the vegetative to reproductive sinks each day. Kernels are allowed to grow until physiological maturity is reached. If the plant runs out of resources, however, growth is terminated prior to physiological maturity. Likewise, if the grain growth rate is reduced below a threshold value for several days, growth is also terminated.

*Management module*

The management module determines when field operations are performed by calling sub modules. Currently, these operations are planting, harvesting, applying inorganic fertilizer, irrigating and applying crop residue and organic material. These operations can be specified by users in the standard 'experiment' input file (Hunt *et al.*, 2001). Users specify whether any or all of the operations are to be automatic or fixed based on input dates or days from planting. Conditions that cause automatic planting within the interval of time are soil water content averaged over a specified

depth (i.e. 30 cm) and soil temperature at a specified depth to be between specified limits. Harvesting can occur on given dates, when the crop is mature, or when soil water conditions in the field are favorable for machine operation. Irrigation can be applied on specific dates with specified irrigation amount or can be controlled by the plant available water. If plant available water drops below a specified fraction of water holding capacity in an irrigation management depth, an irrigation event is triggered. The irrigation amount applied can be either a fixed amount or it can refill the profile to the management depth. Similarly, fertilizer can be applied on fixed dates in specified amounts, or the applications can optionally be controlled by plant needs for nitrogen via the nitrogen stress variable from the Plant module. Crop residue and organic fertilizer, such as manure, is applied either at the start of simulation, after harvesting the crop or on fixed dates similar to inorganic fertilizer applications. These management options allow users a great deal of flexibility for simulating experiments that were conducted in the past for model evaluation and improvement and for simulating optional management systems for different applications. The management file also provides scope to define multiple crops and management strategies for crop rotations and sequencing.

*Pest module*

The Pest module was developed for the CROPGRO models by Batchelor *et al.* (1993), following the approach described by Boote *et al*. (1983, 1993). It allows users to input field observations and scouting data on insect populations or damage to different plant parts, disease severity on different plant tissues, and physical damage to plants or plant components to simulate the effects of specified pest and diseases on growth and yield. Feedbacks on plant growth processes are through leaf area reduction, assimilate loss, loss of leaves, fruit, stems, or roots, and inactivation of the photosynthetic capacity of leaves (Boote *et al.*, 1983).

### 2.1.4 Data requirements

The DSSAT models require the minimum data set for model operation. The contents of such a dataset have been defined based on efforts by workers in IBSNAT and ICASA (Jones *et al.*, 1994; Hunt and Boote, 1998; Hunt *et al.*, 2001). They encompass data on the site where the model is to be operated, on the daily weather during the growing cycle, on the characteristics of the soil at the start of the growing

cycle or crop sequence, and on the management of the crop (e.g. seeding rate, fertilizer applications, irrigations). Required weather data encompass daily records of total solar radiation incident on the top of the crop canopy, maximum and minimum air temperature above the crop, and rainfall. However, it is recognized that all required weather data for a particular site and a particular time period are often not available. In such cases, the integrity of the minimum data set is maintained by calculating surrogate values or using data from nearby sites. To calculate surrogate values, statistics of the climate at a particular site are necessary and may thus be required. The DSSAT–CSM requires information on the water holding characteristics of different soil layers. It needs a root weighting factor that accommodates the impact of several adverse soil factors on root growth in different soil layers, such as soil pH, soil impedance, and salinity. Additional soil parameters are needed for computing surface runoff, evaporation from the soil surface, and drainage (Ritchie, 1972). Initial values of soil water, nitrate and ammonium are needed as well as an estimate of the above– and below–ground residues from the previous crop. All aspects of crop management including modifications to the environment (e.g. photoperiod extension) as imposed in some crop physiology studies, are needed. Typical crop management factors include planting date, planting depth, row spacing, plant population, fertilization, irrigation and inoculation. Plant bed configuration and bund height is also necessary for some crops. The DSSAT–CSM also requires coefficients for the genotypes involved (Hunt, 1993; Ritchie, 1993).

### 2.1.5 Model evaluation

The ultimate measure of a model's performance is the user's satisfaction with both the accuracy of predictions and overall utility of the model. Understandably, such a measure is difficult to quantify and is relevant only to the user that generated the rating. Statistical approaches to quantify the accuracy of model predictions provide standardized measures of model performance. Unfortunately, even these methods do not provide completely clear–cut conclusions about the accuracy of model predictions. Use of vague terms like "fairly close" in instructions for interpreting various measures impart an air of skepticism around the use of some of these methods. Given these caveats, the use of several different measures of performance to evaluate a model may present a more complete picture of model

performance than any single measure and allow the user to weight individual results according to their priorities. Two measures that are commonly reported in the literature are the sample correlation coefficient *r* and coefficient of determination $r^2$. The correlation coefficient provides a measure of the linear relationship or closeness between predicted and observed values. Interpretation of *r* is quite general. An *r* of 1.0 indicates perfect prediction by the model with positive values of *r* indicating some level of a positive correlation between the predicted values ($P_i$) and observed values ($O_i$). Conversely, an *r* of 0.0 indicates no correlation of the model to reality whatsoever and negative values indicate an inverse relationship. The coefficient of determination is informally described as the proportion of the variance of the observed values that can be accounted for by the model. This measure has more utility in that it presents an idea of how thoroughly the model represents the system. Statistical analyses demonstrating the level of significance of *r* only proves that a linear relationship with a non–zero slope exists between $P_i$ and $O_i$ (Snedecor and Cochran, 1989). The validity of this conclusion can come into question if $P_i$ and $O_i$ do not meet the underlying assumptions required for the particular analysis used (Willmott, 1981). In spite of their popularity, these measures provide little detail to characterize the relationship between $P_i$ and $O_i$.

A simple method of visualizing the relationship between $P_i$ and $O_i$ is plotting a scatterplot of $P_i$ (Y–axis) and $O_i$ (X–axis), relative to a line designating a 1:1 relationship. While not quantifiable, some relationships (e.g. consistent under prediction) become apparent. Scatterplots also provide a common sense check for more sophisticated methods of evaluation. If results of a test do not appear consistent with the results of the scatterplot, the test should be re–evaluated. The relationship between $P_i$ and $O_i$ presented in the scatterplot can be quantified using linear regression. The slope of the regression line (*a*) and its Y–intercept (*b*) may provide evidence of systematic error in the model, providing quantities that can be compared across models. A slope of 1.0 with a Y intercept equal to 0.0 indicates perfect fit of the model predictions. These results along with the means ($\overline{P}$ and $\overline{O}$) and standard deviations of the predicted values and observed values should be considered for their own merit as well as their use in calculating other measures when evaluating model performance.

Difference measures, derived from the fundamental quantity ($P_i$–$O_i$) (Willmott, 1982), build on the statistical measures listed above to quantify bias and

average error. Root mean square error (RMSE) describes the average difference between $P_i$ and $O_i$.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \qquad \text{(Eq. 2.1.5.1)}$$

Also, RMSE can be readily compared against the mean of the observed values for comparison of relative error. Both RMSE and its square (mean square error or MSE) can be subdivided into systematic ($RMSE_s$ and $MSE_s$) and unsystematic ($RMSE_u$ and $MSE_u$) components (Willmott, 1981).

$$MSE = \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n} \quad MSE_s = \frac{\sum_{i=1}^{n}\left(\hat{P}_i - O_i\right)^2}{n} \quad MSE_u = \frac{\sum_{i=1}^{n}\left(P_i - \hat{P}_i\right)^2}{n} \qquad \text{(Eq. 2.1.5.2)}$$

N is the number of pairs of predicted and observed data, and $\hat{P} = aO_i + b$. When the systematic component is minimized, the model is predicting at its maximum possible accuracy and the primary source of error is not model–related. An alternative presentation is offered by Roseler *et al*. (1997) where mean square prediction error (MSPE), which has the same mathematical definition as MSE (Neter *et al*., 1990; Roseler *et al*., 1997), is considered as the sum of three components: mean bias $\left(\overline{O} - \overline{P}\right)^2$, line bias $[S_p^2(1–b)^2]$, and random variation around the regression line $[S_o^2(1–r^2)^2]$, where $S_p^2$ and $S_o^2$ are the variances of the predicted and observed values. These measures provide insight not just on the magnitude of error but also hint at the potential sources of error.

Willmott (1981; 1982) proposed another measure of model performance that he called “index of agreement”. This is referred to elsewhere as the d–index. The d–index describes the degree to which the observed data are accurately estimated by the predicted data. More formally, it specifies the degree to which the deviation of the observed data around $\overline{O}$ corresponds with the deviation of the predicted data around $\overline{O}$, both in magnitude and sign.

$$d = 1 - \frac{\sum_{i=1}^{n} \left(P_i - O_i\right)^2}{\sum_{i=1}^{n} \left(\left|P'_i\right| - \left|O'_i\right|\right)^2} \qquad \text{(Eq. 2.1.5.3)}$$

where $P'_i = P_i - \overline{O}$ and $O'_i = O_i - \overline{O}$. Potential values of d range from 0 to 1, with 1.0 indicating perfect agreement between predicted and observed data and 0.0 indicating complete disagreement. The sole assumption is that $\overline{O}$ is free of error so that all error is contained in $P'_i$ and $O'_i$. The equation can be rewritten as

$$d = 1 - \frac{n \cdot MSE}{\sum_{i=1}^{n} \left(\left|P'_i\right| - \left|O'_i\right|\right)^2} \qquad \text{(Eq. 2.1.5.4)}$$

for simplified calculation when MSE is known. The innovation of the d–index is that it responds to both differences between predicted and observed data as well as some changes in proportionality (Willmott, 1981). The d–index is an improvement on the simple *r*; still, it is not an absolute measure of performance. As with the aforementioned methods, the d–index should be evaluated in the context of knowledge of natural variations in the system being modeled, the capabilities of the model, and an awareness of the amount of potential error in the observed values used in the comparison. No one of these approaches will be best in all situations, reviewing several of these measures together will provide a more complete description of model performance. The results should also be viewed in the context of the intended use of the model. If the model is to be used to demonstrate the response to a change in the environment to a class of students, a model that predicts a response of the correct direction but severely under or over–predicts the magnitude may be preferable to a more accurate model if the latter is more difficult for the students to use. Users must decide for themselves what level of performance is acceptable. Likewise, individuals will have their own views of which approach is most appropriate to their interests.

## *2.2 Rapeseed*

### 2.2.1 Yield and its components

*Growth and development*

In general, the life cycle of rapeseed can be divided into seven stages: germination/emergence, leaf development, stem elongation, inflorescence emergence, flowering, development of seed and ripening (Sylvester–Bradley and Makepeace, 1984). In particular, the latter three stages overlap considerably, because vegetative, generative and reproductive organs develop concomitantly.

A standardized growth stage scale developed by BASF, Bayer, Ciba–Geigy and Hoechst called the BBCH decimal system provides an accurate and simplified approach to describing rapeseed growth stages (Lancashire *et al.*, 1991).

*Growth Stage 0: Germination and seedling emergence*

During the early stages of germination and seedling emergence, distribution of plants per unit area is especially important for yield stability (Sierts *et al.*, 1987). The percentage germination of rapeseed in a standard test correlated poorly with field performance. However, the mean time to germination revealed highly significant correlations with field performance and seed yield (Larsen *et al.*, 1998). The considerable variation in the emergence of seedlings depends on moisture, temperature and the structure of soil. Although there was considerable genetic variation in the time taken for seeds to germinate at low temperature, this was not related to the growth performance of selected populations (Witcombe and Whittington, 1971; Acharya *et al.*, 1983; Kondra *et al.*, 1983; King *et al.*, 1986).

*Growth Stage 1: Leaf development*

Upon emergence, four to 15 days after seeding, the seedling develops a short 1.25 to 2.5 cm stem. The cotyledons at the top of the hypocotyl expand, turn green and provide nourishment to the growing plant (Allen *et al.*, 1971). The cotyledons of *B. napus* seedlings are smooth on the underside.

**Table 2.5** BBCH growth stage scale – oilseed rape.

| **0** | **Germination** | **1** | **Leaf development** | **2** | **Formation of side shoots** | **3** | **Stem elongation** | **4** | **Development of harvestable vegetative plant parts** |
|---|---|---|---|---|---|---|---|---|---|
| 00 | Dry seed | 10 | Cotyledons completely unfolded | 20 | No side shoots | 30 | Beginning of stem elongation no internodes | 40 | – |
| 01 | Beginning of seed imbibition | 10 | First leaf unfolded | 21 | Beginning of side shoot development first | 31 | One visibly extended internode | 41 | – |
| 02 | – | 12 | Two leaves unfolded | 22 | Two side shoots detectable | 32 | Two visibly extended internode | 42 | – |
| 03 | Seed imbibition complete | 13 | Three leaves unfolded | 23 | Three side shoots detectable | 33 | Three visibly extended internode | 43 | – |
| 04 | – | 14 | Four leaves unfolded | 24 | Four side shoots detectable | 34 | Four visibly extended internode | 44 | – |
| 05 | Radicle emerged from seed | 15 | Five leaves unfolded | 25 | Five side shoots detectable | 35 | Five visibly extended internode | 45 | – |
| 06 | – | 16 | Six leaves unfolded | 26 | Six side shoots detectable | 36 | Six visibly extended internode | 46 | – |
| 07 | Hypocotyl with cotyledons emerged from seed | 17 | Seven leaves unfolded | 27 | Seven side shoots detectable | 37 | Seven visibly extended internode | 47 | – |
| 08 | Hypocotyl with cotyledons growing towards soil surface | 18 | Eight leaves unfolded | 28 | Eight side shoots detectable | 38 | Eight visibly extended internode | 48 | – |
| 09 | Emergence: cotyledons emerged through soil surface | 19 | Nine or more leaves | 29 | End of side shoots development: 9 or more side shoots detectable | 39 | Nine visibly extended internode | 49 | – |
| **5** | **Inflorescence emergence** | **6** | **Flowering** | **7** | **Development of fruit** | **8** | **Ripening** | **9** | **Senescence** |
| 50 | Flower buds present, still enclosed by leaves | 60 | First flowers open | 70 | – | 80 | Beginning of ripening: seed green, filling pod cavity | 90 | – |
| 51 | Flower buds visible from above (“green bud”) | 61 | Ten percent of flowers on main raceme open, main raceme elongating | 71 | Ten percent of pods have reached final size | 81 | Ten percent of pods ripe, seeds black and hard | 91 | – |
| 52 | Flowers buds free, level with the youngest leaves | 62 | – | 72 | – | 82 | – | 92 | – |
| 53 | Flower buds raised above the youngest leaves | 63 | Thirty percent of flowers on main raceme open | 73 | Thirty percent of pods have reached final size | 83 | Thirty percent of pods ripe, seeds black and hard | 93 | – |
| 54 | – | 64 | – | 74 | – | 84 | – | 94 | – |
| 55 | Individual flowers buds (main inflorescence) visible but still closed | 65 | Full flowering: 50% of flowers on main raceme open, older petals falling | 75 | Fifty percent of pods have reached final size | 85 | Fifty percent of pods ripe, seeds black and hard | 95 | – |
| 57 | Individual flower buds (secondary inflorescence) visible but still closed | 67 | Flowering declining: majority of petals fallen | 77 | Seventy percent of pods have reached final size | 87 | Seventy percent of pods ripe, seeds black and hard | 97 | Plant dead and dry |
| 58 | – | 68 | – | 78 | – | 88 | – | 98 | – |
| 59 | First petals visible, flower buds still closed | 69 | End of flowering | 79 | Nearly all pods have reached final size | 89 | Fully ripe: nearly all pods ripe, seeds black and hard | 99 | Harvested product |

The growing point of rapeseed is above the soil, between the two cotyledons and makes rapeseed seedlings more susceptible than cereals to spring frosts, soil drifting, insects and hail or any other hazard that results in the destruction of the seedling below the cotyledons. Heat canker may occur when the bare soil temperature becomes so high as to burn the hypocotyl at the soil surface (Daniels *et al.*, 1986).

The juvenile growth phase of winter oilseed rape lasts from emergence through cessation of growth in winter and stem elongation to the start of flowering.

Rapeseed plants have a tap root system. Rooting depth varies from 3 to 5 cm at emergence. The root system continues to develop with secondary roots growing outward and downward from the taproot. Root growth is due to cell division and enlargement at the tip of the root. Root development is relatively constant averaging nearly 2 cm per day as long as good soil moisture exists (Toniolo and Mosca, 1986). Where soil water and nutrients are abundant, the balance of root to stem and leaf growth typically shifts in favour of stem growth at the expense of roots. When water is limiting, the opposite usually occurs. Root and stem growth complement one another by adjusting their relative size to meet the basic requirements of the whole plant in response to climatic and soil conditions. With moisture stressed rapeseed, roots account for about 25% of plant dry matter at stem elongation compared to about 20% for unstressed plants. At peak flowering and maximum stem length, roots will have reached about 85% of their maximum depth. Root depth, like plant height, will vary from 90 to 190 cm but will average about 140 cm at maturity. The root system varies with soil type, moisture content, temperature, salinity and soil physical structure (Daniels *et al.*, 1986).

Four to eight days after emergence the seedling develops its first true leaves. The first true leaf to develop and fully expand is frilly in appearance. The plant quickly establishes a rosette with older leaves at the base increasing in size, and smaller, younger leaves developing in the centre. *B. napus* plants develop larger rosettes of up to six waxy, blue–green leaves. To withstand subsequent periods of temperatures below freezing, individuals should reach the 6±8 true–leaf stage, have a root head diameter of >5 mm and a shoot length of <20 mm (Scott *et al.*, 1973a, 1973b; Vullioud, 1974; Schröder and Makowski, 1996). In autumn, the potential for flowering branches is also determined by the number of leaf axils (Mendham and Scott, 1975). The onset of generative development has already occurred before or

during winter. Flower initiation usually takes place from early November (when sown in August) to mid–December (when sown in September) (Geisler and Henning, 1981b; Tittonel *et al.*, 1982; Tittonel, 1988). The onset of flower initiation can have strong influence on flower, pod and seed number (Tayo and Morgan, 1979; Mendham *et al.*, 1981a). Low temperature and low light intensity during the winter cause a dramatic loss of foliage and, thus, of stored N as well as a reduced LAI (about 0.5± 1.0) (Diepenbrock, 1981; Grosse *et al.*, 1992a; Colnenne *et al.*, 1998). There is a positive correlation between seed yield and maximum leaf area index (LAI). A LAI of about four is required for the crop canopy to intercept about 90% of the incoming solar radiation. The larger the leaf area the crop can expose to the sun, the more dry matter the crop can produce per day. The more dry matter, the higher the potential yield (Freyman *et al.*, 1973). Researchers report that the maximum LAI for *B. napus* is between 3 and 6 (Morrison *et al.*, 1992). Although plants have a substantial capacity to compensate for damage, an optimal stand establishment before the onset of winter is a prerequisite for both high yield and high yield stability (Sierts *et al.*, 1987). For example, Stoy (1983) created artificial stands and gradually reduced plant density by hand during winter to simulate plant loss. Individual plants of the control (45 plants $m^{-2}$ in autumn; 43 plants $m^{-2}$ in spring) yielded 14.1 g. In contrast, there was a dramatic decrease to 7.8 g per plant when 185 plants $m^{-2}$ sown by the end of August were thinned to 43 plants $m^{-2}$.

There is no definite number of leaves produced by a rapeseed plant. A rapeseed plant under good growing conditions normally produces nine to 30 leaves on the main stem depending on variety and growing conditions. The maximum area of individual leaves on the plant in the absence of stress is around 250 $cm^2$ (Morrison *et al.*, 1992). Count the leaves of a rapeseed plant when it has become visibly separated from the terminal bud. During the rosette growth stage the stem length remains essentially unchanged although its thickness increases.

Leaf is a major source of photosynthesis until full flowering; thus, it is highly important that the rates of leaf emergence and expansion are high. Dry matter produced during this stage later supports pod growth by mobilising the transiently stored substances (Brar and Thies, 1977; Major *et al.*, 1978). This is underlined by Habekotté (1993) who stressed the relevance of the total assimilate availability during the important phase of pod growth. A quantitative analysis of pod formation confirmed the linear relationship between the cumulative production of dry matter

until flowering and pod density. Accordingly, close genotypic correlations were found between the duration of the leaf area index (LAID) until flowering and seed yield (Grosse *et al.*, 1992b).

*Growth Stage 3: Stem elongation*

Stems display the leaves to sunlight and air. Rapeseed plant stems are also important photosynthetic structures throughout the period of pod and seed growth. Stem elongation (GS 30) overlaps leaf development and normally occurs earlier than GS 19. Maximum stem length (GS 39) overlaps flower development and is reached at peak flowering (GS 65) (Evans, 1984; Mendham and Salisbury, 1995). As stems elongate, roots continue to grow deeper. The vegetative stages, or days from seeding to first flower, can range from 40 to 60 days, depending on date of seeding and growing conditions (Toniolo and Mosca, 1986). *B. napus* plants grow tall (75 to 175 cm). Stem diameter and height are influenced by seeding date, moisture, variety, soil fertility and plant population. Plants in low–density crops have thicker stems and are more resistant to lodging. Plants in high–density crops are thinner and more prone to lodging (Mendham and Salisbury, 1995). Lodging aggravates the problem of uneven pod maturity and creates an ideal micro–environment for the spread of diseases such as sclerotinia and alternaria. Disease infection reduces the photosynthetic capacity of the stems and pods, reducing yields.

*Growth Stage 5: Inflorescence emergence*

Lengthening days and rising temperatures trigger bud formation. Flower development growth stages (GS 50–65) overlap stem development (GS 30–39). Initially flower buds (GS 50) remain enclosed during early stem elongation (GS 31) and can only be seen by peeling back young leaves. As the stem elongates a cluster of flower buds can be easily seen from above but are still not free of the leaves. This is known as the green bud stage. As the stem rapidly lengthens, the buds become free of leaves and the lowest flower stalks extend so that the buds assume a flattened shape. The remaining leaves attached to the main stem unfold as the stem lengthens and the small stalks holding the first unopened flower buds become more widely spaced (Bouttier and Morgan, 1992). The lower flower buds are the first to become yellow, signalling the yellow–bud stage (McGregor, 1981). Secondary branches arise from buds that develop in axils of upper leaves and occasionally from axils of some

lower leaves on the main stem. These secondary branches develop one to four leaves and a flower bud cluster. The rapeseed plant initiates many more inflorescences than it can support, then aborts back according to the plants set carrying capacity and environmental conditions. The ability to produce secondary branches is useful as it allows the crop to compensate for poor stand establishment and damage due to hail, pests and diseases. Development of branches is not fixed until the end of flowering. Removal of branches by hail can initiate replacement. Environmental stress can reduce the degree of branching and if the second to fourth primary branches (from the top) are affected, total flower production and therefore total seed yield can be seriously reduced (Tayo and Morgan, 1975; 1979). *B. napus* plants have a distinct main stem with few secondary branches. *B. napus* plants, in an average uniform stand, will average from four to six branches per plant. However, individual plants can range from two to nine branches (McGregor, 1981; Smith and Scarisbrick, 1990). Low plant populations produce more branches per plant compared to high plant populations. The main stem reaches 30 to 60% of its maximum length just prior to flowering. Also, between 30 to 60% of the plant's total dry matter production will have occurred at this time, depending upon growing conditions (Tayo and Morgan, 1979).

Maximum leaf area is usually reached near the beginning of flowering and then begins to decline with the loss of lower leaves. The leaves, especially the upper ones at this stage, are the major source of food for the growth of stems and buds. Rapid development and growth of a large leaf area, which is maintained well beyond the start of flowering, strongly influences pod set and early seed development on the main stem and the first few secondary branches (Pechan and Morgan, 1985; Daniels *et al.*, 1986). The development and maintenance of a large leaf area after the start of flowering is largely dependent on proper seedbed preparation combined with adequate moisture, temperature and nutrients that promote rapid, uniform emergence and growth (Evans, 1984).

*Growth Stage 6: Flowering*

*B. napus* varieties are self–pollinated and do not need pollinating agents such as wind and insects. About 70 to 80% of the seed produced is from self–pollination (Toniolo and Mosca, 1986). At flowering in *B. napus*, the buds are normally borne above the open flowers. The shape of the leaves on the flowering stalk only partially

clasps the stem. Flowering begins with the opening of the lowest bud on the main stem and continues upward with three to five or more flowers opening per day. Flowering at the base of the first secondary branch begins two to three days after the first flower opens on the main stem (McGregor, 1981). Under reasonable growing conditions, flowering of the main stem will continue from 14 to 28 days (Toniolo and Mosca, 1986). Full plant height (GS 39) is reached at peak flowering (GS 65) due to the overlap of growth stages. Flowers begin opening early in the morning and, as the petals completely unfold, pollen is shed and dispersed by both wind and insects. Flowers remain receptive to pollen for up to three days after opening. If favourable, warm, dry weather occurs, nearly all the pollen is shed the first day the flower opens. In the evening, the flower partially closes and opens again the following morning. Fertilization occurs within 24 hours of pollination. After pollination and fertilization, the flower remains partially closed and the petals wilt and drop (two to three days after the flower opened) (Eisikowitch, 1981). The young pod becomes visible in the centre of the flower a day after petals drop. During flowering, the branches continue to grow longer as buds open into flowers and as flowers develop into pods. In this way, the first buds to open become the pods lowest on the main stem or secondary branches. Above them are the open flowers, and above them, the buds which are yet to open. All of the buds that will develop into open flowers on the main stem will likely be visible in *B. napus* within three days after the start of flowering (McGregor, 1981).

Rapeseed plants initiate more buds than they can develop into productive pods. The flowers open, but the young pods fail to enlarge and elongate, and eventually fall from the plant. The abortion of flowers and pods is natural. Both flowers and seeds can undergo substantial abortion depending on the carrying capacity established by leaf, stem and branch growth plus environmental stress imposed during flowering and seed set. During flowering the plant can adjust yield based on the number of flowers produced and pollinated.

Under stress, the number of branches that produce flowers may be reduced and the number of flowers on each branch may decline. Flowers that are open during heat stress may fail to pollinate. Normally, fertility of flowers that open later will be unaffected if stress has been alleviated. Areas on the main stem or branches with no pod development are symptoms of stress. Under severe stress, loss of unopened buds increases, signalling the end of flowering (Smith and Scarisbrick, 1990). If the severe

stress occurred at early flowering the plant may resume flowering through increased branching if very favourable conditions return. Studies have shown that only 40 to 50% of the flowers produced on a plant develop productive pods, which are retained until harvest (Toniolo and Mosca, 1986).

At the peak of flowering rapeseed produces a bright yellow layer of flowers, at least 30 cm thick, which forms an effective reflecting and absorbing surface for solar radiation at the top of the crop. Studies have found that flowers reflect or absorb about 60–65% of incoming radiation that could have been utilized by the photosynthetic active tissues of the plant (Bilsborrow and Norton, 1984; Yates and Steven, 1987; Leach *et al.*, 1989). At the same time, photosynthesis of the crop decreases by 40% (Robelin and Triboi, 1983). Research studies comparing a normal flowering variety with an apetalous variety at peak flowering have shown that solar radiation into the canopy increased by 30% when plants had no flower petals (Rao *et al.*, 1991; Mendham *et al.*, 1991). The main reason for the decrease in LAI after floral initiation is the reduction of radiation into the leaf canopy caused by flower petals. This shading results in senescence of active green leaves. Therefore, apetalous varieties should have a greater photosynthetic capability through increased radiation into the crop canopy at the critical stage for developing pods and seeds (Rao *et al.*, 1991).

From about two weeks after full flowering, the total net $CO_2$ fixation by pod hulls exceeds that of leaves, because pods are exposed to much higher radiation than leaves (Gammelvind *et al.*, 1996). While the carbon balance changes during this phase, competition for assimilates is responsible for loss of buds, flowers, pods and seeds (Keiller and Morgan, 1988; Diepenbrock and Grosse, 1995). These processes are closely related to positional effects on the plant (Williams, 1978; Williams and Free, 1979). Low–ordered, i.e. late–flowering, branches generally produce fewer flowers and pods. Moreover, buds, flowers and pods are lost more quickly on these branches (Tayo and Morgan, 1975). Thus, a potential for compensating for the generative or reproductive organs lost as a result of environmental stress declines gradually with flowering (McGregor, 1981; Tommey and Evans, 1992).

*Growth Stage 7: Development of seed*

By mid–flower, when lower pods have started elongating, the stem becomes the major source of food for plant growth, with a reduced amount from the declining

leaves and a small amount from the developing pods. There is competition for the food supply between flowers and pods on the same branch, as well as between branches. The early developed pods have a competitive advantage over later formed pods. Flowering on the later developing secondary branches may continue for some time after the main stem has finished flowering. Older pods at the base of the flowering branches are well along in development while new flowers are still being initiated at the tips. At this stage, the stem and pod walls are both major sources of food for seed growth since the pod photosynthetic surface area has greatly increased (Major *et al.*, 1978). During the first couple of weeks of seed development, the seed coat expands until the seed is almost full size. The seed at this stage is somewhat translucent and resembles a water–filled balloon. The seed's embryo now begins development and grows rapidly within the seed coat to fill the space previously occupied by fluid; seed weight increases (Daniels *et al.*, 1986). Any stress leading to a change in the supply of food can abort pods or reduce the number of seeds in each pod. The stress may be internal where the plant is unable to take up soil water available to it or to generate food supplies necessary for seed filling. The stress can be external where soil water is limiting or temperatures excessive for optimal crop development (Chongo and McVetty, 2001). The number of seeds that develop in each pod will be influenced by the availability of plant food supplies at the time when seed expansion occurs. Lack of plant food supplies at this growth stage will result in smaller pods with fewer, lighter seeds, especially in the later secondary branches and tops of branches. Substantial stress at seed expansion leads to shorter pods and/or lack of expansion around missing seeds. Segments of the pods will not expand normally with little or no sign of seed remnants inside the pod (Clarke and Simpson 1978a, 1978b; Clarke, 1979). Plants under stress redirect food supplies from stems and pods to those seeds that are left. The only way a plant can respond to more favourable conditions late in the growing season is by producing larger seeds. When severe stress occurs later in the filling process, the pod appears normal because the seed expanded normally and then started to die off resulting in a shrivelled seed coat with little or no evidence of having started the seed filling process (Campbell and Kondra, 1977; 1978). Once seed expansion is complete, seeds are more resistant to loss from stress, but losses can occur if stress is severe. The plant attempts to redirect food supplies to seeds that continue filling. Pods show no external signs of stress, but affected seeds may be visibly shrivelled within the pod.

Even where shrivelling is not evident, due to reduced food supplies, seed size will be smaller and a larger portion of seeds will have wrinkled seed coats. *B. napus* pods are large, with a medium length beak (Rood *et al.*, 1984). Normally a pod contains 15 to 40 seeds. *B. napus* seeds are generally large at 3.0 to 5.5 g (1000 seeds weight) (Toniolo and Mosca, 1986).

Post–anthesis growth of the whole canopy is significantly supported by growth of the pods and seed filling. Seed yield is linearly related to PAR that is intercepted during the pod filling phase. Andersen *et al.* (1996) reported an apparent seed dry matter: radiation quotient of 2.47 g $MJ^{-1}$ during this period. However, under severe drought stress during the flowering phase, up to 65% of the assimilates produced during pod filling were found in the straw, because the sink size of seeds was limited. Furthermore, Hansen (1994) showed that N fertilisation had a strong impact on the RUE for growth of the seeds. In this investigation, the dry matter of the seeds was related to the total incoming PAR during the whole growing season. N deficiency (0 kg N $ha^{-1}$) led to a RUE of 0.23 g seed dry matter $MJ^{-1}$ compared to 0.50 g $MJ^{-1}$ found at full N supply (240 kg N $ha^{-1}$). In individual pods, developing seeds locally induce growth of pod tissue, representing a major part of the assimilating surface of the crop (Pechan and Morgan, 1985) maintaining a close relationship between the capacity of sink and source during reproductive growth. While long pods generally contain more seed, this is largely the response of pod growth to seed content. During maturation, pod hulls transfer transiently stored carbohydrate to seeds. Exportation from the hulls starts about two weeks after fertilisation and can account for 60% of the total assimilate for seed filling of detached pods (Nitsch, 1976; Diepenbrock and Geisler, 1978). In crop stands, however, the overall mobilisation of reserve carbohydrates from roots, stems, leaves and pod hulls contributed at the most 12±17.5% to the final yield (Quillere and Triboi, 1987; Habekotté, 1993). It is likely that translocation of N compounds governs ontogenesis of pods and seeds. On an average, the amount of N mobilised from stems and pod hulls represents about 70% of the N present in these organs at mid–flowering. At harvest, 10% of the total N in the shoot is located in stems and pod hulls and the remaining N is located in the seed (Schjoerring *et al.*, 1995). Although several factors during flowering can limit the yield, winter rapeseed has the potential for growth after flowering, which compensates for losses of buds, flowers and pods (Boelcke and Vietinghoff, 1987). For example, this is most important for

practical farming when the crop is subjected to damage to flower buds caused by *Meligethes aeneus* (Sylven and Svensson, 1976). Even air pollution (ozone) was shown to induce compensatory responses to branching (Ollerenshaw *et al.*, 1999). In case of a frost event at the beginning of flowering, branching increases, and the flowering period lasts longer, resulting in more pods that are poorly filled, because yield is compensated by pods of the lower branches, which yield relatively low (Lardon and Triboi–Blondel, 1995). In general, the terminal raceme and the uppermost branches produce a comparatively larger number of productive pods. Under experimental conditions, the loss of flowers from lower–order branches can be tolerated or may even be advantageous, because these branches are less productive (Daniels *et al*., 1986). Accordingly, the removal of flowers from lower ordered branches usually did not significantly reduce the total seed yield (Tommey and Evans, 1992). Consequently, the production of lower branches during yield development should be hindered so as to increase the overall production capacity of the stand (Diepenbrock and Geisler, 1979). In designing a physiologically based crop ideotype, the simulation study by Habekotté (1997a) reveals that a high yielding crop should combine certain important characteristics such as early flowering, LAI of about three, small petals or apetalous flowers, a high rate of seed set and erect clustered pods, which are all related to better absorption of light and to synchronisation of the capacity of the source and sink. In addition, Tommey and Evans (1992) proposed that breeding programmes should select for a limited number of highly productive pod bearing branches. As outlined by Léon and Becker (1995), however, only a limited number of physiologically based breeding goals are independent of environmental conditions. The most promising traits to be introduced into breeding material relatively easily are the apetalous flower and long pods. Both traits are easily inherited. Nevertheless, the effect of pod length on yield depends to a great extent on the genetic background (Chay and Thurling, 1989a, 1989b).

*Growth Stage 8: Ripening*

At the stage where seeds in the lower pods have turned green, most of the leaves on the plant have yellowed and fallen from the plant. The pod walls have become the major source of food although the stem is still important. The pods, besides being major food producers, are also major food users from other sources for seed development. About 35 to 45 days after the flower opens seed filling is

complete (Thurling, 1974a). The firm green seed has adequate oil and protein reserves to support future germination and seedling growth. The stems and pods turn yellow and progressively become brittle as they dry. Usually the earliest formed pods are the largest and develop more and larger seeds. Immature seeds, when filled, contain about 40 to 45% moisture. The seed coat then begins to turn from green to yellow or brown, depending on the variety. Seed moisture is rapidly lost at a rate of 2 to 3% or more per day, depending on growing conditions. At 40 to 60 days after first flower or 25 to 45 days after the end of flowering, the seeds in the lower pods will have ripened and fully changed colour. As the seed coat changes colour so does the seed. The embryo, which fills the entire seed, begins to lose its green colour. When completely mature the seed is uniformly bright yellow in colour. When 30 to 40% of the seeds on main stem of a plant have begun to change seed coat colour (black or yellow), seeds in the last formed pods are in the last stages of filling. The majority of seeds have reached physiological maturity and the average seed moisture is about 30 to 35% (Thurling, 1974b). This is the optimum stage for swathing. Swathing before physiological maturity can result in reduced yields due to incomplete seed development. Although the potential number of pods per plant and seeds per pod is set at flowering, the final number is not established until a later stage (Thurling, 1974b). Seed filling requires adequate soil moisture and nutrients. Seed abortion, or reduction in seed weight, can be caused by anything that interferes with plant functions during this time. In rapeseed, the seed accounts for about 23 to 31% of the total plant dry matter produced, depending upon growing conditions. The leaves, stems and especially pod surface areas must be kept free from disease, insect or weather damage. Anything that stresses or reduce the food production capacity of these plant surfaces may lead to a reduction in seed yield. When all the seeds in all pods have changed colour, the plant dies. Mature pods easily shatter (split along the centre membrane) and the seed lost (Thurling 1974a, 1974b).

# 3. MATERIALS AND METHODS

## *3.1 Approach for model adaptation*

To adapt CROPGRO for rapeseed, two approaches to develop the required species file and cultivar traits were followed, based on:

- Values and relationships reported from the literature and
- Comparison to observed experimental growth analyses data on rapeseed grown in Sardinia, Italy, during a season and in two different representative sites.

In addition, literature sources, for deriving relationships needed for the species file and described the process of developing species and cultivar coefficients from experimental data, was documented.

Due to the similarity between rapeseed and soybean, starting point was the CROPGRO–Soybean model version 4.0.2 (Wilkerson *et al*., 1983) as suggested by model developers (J.W. Jones and Richard Ogoshi, p.c.).

A systematic procedure was followed, according to that described by Boote (1999):

1) Values such as tissue composition, base and optimum temperature for processes, and critical N concentrations for photosynthesis were obtained from the literature. Some relationships obtained from the literature were subsequently modified upon comparison to field data.
2) Photothermal day (PD) threshold values so as to correctly predict crop life cycle, anthesis and maturity dates, each in sequence, were adjusted. This process was extended by comparison to data on similar cultivars in France and by comparison to observed phenology for sowing dates of the specific cultivar in Spain.
3) Predicted biomass accumulation and leaf area index (LAI) were compared to observed values, using actual weather and management input data, and used for calibration of photosynthesis and leaf growth parameters.
4) Comparisons of predicted vs observed timing of pod growth was made in addition to evaluating dry matter partitioning among leaf, stem, and pod components. Features such as timing from anthesis to first pod, anthesis to first seed, and duration of pod addition were

adjusted as well as allocation among leaf, stem, and root before reproductive growth.

5) Seed size, seeds per pod, and single–seed growth rate and duration were adjusted to reproduce correct seed size, seed growth duration, and threshing percentage.

There was considerable iteration between the third, fourth, and fifth steps out lined here where comparisons were made visually to observed growth analyses data.

### *3.2 Experimental sites and initial conditions*

Two field experiments, with a common experimental protocol, were carried out at two sites, Ottava (81 m above sea level, latitude 40° 46' N and longitude of 8° 29' E) and Ottana (187 m above sea level, latitude 39° 25' N and longitude 9° 31' E), in the 2007–2008 and 2008–2009 growing seasons. In 2008-2009 due to adverse weather conditions, sowings were done late in the season and only phenology was monitored. The sites were different for geographical, litho–pedologic and thermopluviometric conditions. Both sites, having similar latitude, showed the same photoperiodic trend.

#### 3.2.1 Ottava (SS)

At Ottava, the experiment was carried out at the Experimental Farm of the University of Sassari in the North–West of Sardinia, near Sassari, Italy.


**Figure 3.1** Location of the Ottava site.

The most common soils in the area are classified as Eutric and Vertic Cambisols (soils with pedogenetic structure in depth and weakly differentiated profile), Eutric Leptosols (shallow soils) and Leptic Cambisols according to the WRB (World Reference Base for Soil Resources, 1998). The most common land uses are cereal crops, pastures and Mediterranean maquis.

The site has a typical Mediterranean climate with mean annual rainfall over 50 years (1958–2008) of 535 mm, mainly occurring in October, November and December. Rainfall during summer do not exceed 30 mm with lowest values in July. Mean annual temperature ranging from 9.5 °C (January) to 23.7 °C (August) that are the coldest and warmest month respectively. Minimum temperature values less then 0 °C are not common, and the mean of the annual minimum temperature is about 6 °C.

### 3.2.2 Ottana (NU)

The field study was conducted in a private farm at Ottana located approximately 25 km west of the town of Nuoro, in Central Sardinia, Italy.


**Figure 3.2** Location of the Ottana site.

The area has been traditionally managed for arable cropping of cereals (wheat, barley), permanent pastures and temporary hay grassland. However, progressive land abandonment since the second half of the 20$^{th}$ century has led to an extensive rangeland landscape.

In the Ottana's area, most widespread soil typological unit consists of little deep soils with texture from sandy loam to loamy clay. Soils are poorly drained and classified as Rock Outcrop and Lithic Xerorthents according to Soil Taxonomy (USDA, 1999).

Climate is Mediterranean semiarid with warm summers, cold winters, and a high water deficit from May to September. Mean annual temperature is 17.1 °C (1994–2008), mean minimum temperature is 10.0 °C, and mean maximum temperature is 24.6 °C. Annual mean thermal excursion is of 17.8 °C (8.1 °C in January and 25.9 °C in August). Precipitation is distributed fairly evenly throughout the winter season and the annual mean value is 579 mm.

### 3.2.3 Trial management

The experimental field of Ottava was cropped with durum wheat (*Triticum durum* L.) in 2006, while Ottana site in 2006 was uncultivated. Land preparation was done as per the normal procedure for yield trials; the field was ploughed with a disc plough to create suitable conditions for good soil–seed contact. Seed bed preparation was carried out before sowing by a disk harrow. The agronomic practices listed in table 3.1 were applied to the experiment.

**Table 3.1** Crop management information for the fields experiment on the experimental farm in the years 2007–2008.

| Activities | | | Ottava (SS) | Ottana (NU) |
|---|---|---|---|---|
| Land preparation | | | Ploughed with disc plough<br>Harrowed with disc harrow | Ploughed with disc plough<br>Harrowed with disc harrow |
| Date of planting | | | 13th November 2007 | 9th November 2007 |
| Depth of planting | | | 20 to 40 mm | 20 to 40 mm |
| Row spacing | | | 0.17 m | 0.17 m |
| Seeding rate | | | 8.0 kg $ha^{-1}$ | 8.0 kg $ha^{-1}$ |
| Fertilizer applied | N | Sowing | 36 kg $ha^{-1}$ | 36 kg $ha^{-1}$ |
| | | Vegetative stage | 92 kg $ha^{-1}$ | 92 kg $ha^{-1}$ |
| | P | Sowing | 92 kg $ha^{-1}$ | 92 kg $ha^{-1}$ |
| | | Vegetative stage | 0 kg $ha^{-1}$ | 0 kg $ha^{-1}$ |

A variety of rapeseed (Kabel), was sown in the first week of November 2007 using 0.17 m row spacing. Cultivar was selected from preliminary variety trials that tested several rapeseed genotypes for potential differences in yield in Mediterranean environment. Kabel is an alternative cultivar, very early maturing, with short compact stature. A seeding rate of 8 kg $ha^{-1}$ was adopted using a conventional seed drill. Fertilization was set up to 132 kg $ha^{-1}$ N and 92 kg $ha^{-1}$ of $P_2O_5$. The nitrogen was applied as diammonium phosphate (18% N, 46% $P_2O_5$) and urea (46% N) in two dressings; at sowing and at the beginning of stem elongation respectively. In Ottava, weeds were controlled by an application of a pre–emergence herbicide (a.p. Metazachlor). Fungicides and pesticides were applied as recommended for a full

protection of the crop from the prevalent pests and diseases. In Ottana soils had never been planted with oil seed crops before, as consequence, weed and pest control was not performed.

### *3.3 Measurements*

#### 3.3.1 Soil and weather data

Soil characterization was obtained by collecting soil samples, from four different depths (0–15 cm, 15–30 cm, 30–60 cm, 60–90 cm), in November 2007 prior to sowing. All samples were analyzed for texture, pH, organic matter, exchangeable potassium (K) and phosphorus (P), nitrate ($NO_3^-$) and ammonium ($NH_4^+$) concentrations by the Department of Agronomy Science Laboratories. In Ottava, the resulting soil was classified as sandy–clay loam with a depth of about 0.8 m with underlying layers of limestone (Typic Xerochrepts). The mean water contents at field capacity (–0.02 MPa) and at permanent wilting point (–1.5 MPa) were 22.4% and 11.9% by weight, respectively. pH ($H_2O$) ranging from 8.3 to 8.4, organic carbon ranging from 1.1 to 1.3%, nitrogen ranging from 0.10 to 0.12%, and phosphorus–Olsen ranging from 1.0 to 3.6 ppm. In Ottana, the soil of the experimental site was classified as sandy–clay loam, representative of the Ottana Plan, mainly characterized by neutral pH and low fertility, but also by deep clay soil layers that are responsible for diffuse waterlogging in depressed areas. pH ($H_2O$) ranging from 6.3 to 6.5, organic carbon ranging from 1.0 to 1.2%, nitrogen ranging from 0.13 to 0.15% and phosphorus–Olsen ranging from 1.9 to 2.8 ppm.

At Ottava, weather data (daily maximum and minimum air temperature, rainfall and solar radiation) were recorded on site from an agro–meteorological station of the Sardinia Regional Environmental Protection Agency (ARPAS). At Ottana, weather data were obtained from a meteorological station (ARPAS) far a few kilometres from the experimental site.

### 3.3.2 Plant growth and development

Data were collected on plant phenology, biomass accumulation and seed yield.

*Phenology*

After emergence, three permanent sampling areas (10 plants each) were chosen for systematic phenological observations according to the BBCH scale (Lancashire *et al.*, 1991). Vegetative and reproductive stages recorded were:

- Germination (00-09 BBCH code);
- Leaf development (10-19 BBCH code);
- Stem elongation (30-39 BBCH code);
- Inflorescence emergence (50-59 BBCH code);
- Flowering (60-69 BBCH code);
- First pod occurrence (71-73 BBCH code);
- Full pod (75 BBCH code);
- First seed occurrence (80-83 BBCH code);
- Full seed (85 BBCH code);
- Physiological maturity and (89 BBCH code);
- Harvest maturity (99 BBCH code).

In 2008 at full flowering (65 BBCH code), plant height was measured in the sampling areas.

*Dry matter accumulation and Leaf Area Index*

Dry matter accumulation of stems, petioles, leaves, flowers, and pods was measured and leaf area recorded at 4–5 weeks intervals based on sampling of 0.50 $m^2$ of plant material. All of the samples components (leaves, stems, inflorescences and pods) and remaining plants were dried separately to constant weight in a convective oven at 80 °C for 72 h.

Leaf area was determined with a LI–COR planimeter model LI–3000 (Li–Cor, Lincoln, Nebraska, USA). Leaf Area Index (LAI) was assessed from the leaf area and ground area from which the samples were taken.

Top dry matter was calculated as the sum of leaf, stem, inflorescences and pods dry matters.

Specific leaf area (SLA) was calculated for all leaves per sampling area, as the ratio of leaf area to leaf dry mass (first, the leaf area was determined with the LI 3000 leaf area meter, then, the dry mass of these leaves was determined after oven drying for 72 h at 80 °C).

*Seed yield and Harvest Index*

At harvest, three samplings areas (1 $m^2$ each) per field were randomly chosen and plants were cut at ground level. The number of plants in each sampling area was counted to determine the plant density at harvest. Samples were dried at 70 °C to a constant weight. After drying, seeds of each sample were separated and weighed. Harvest Index was obtained as the ratio of seed weight to the total above ground biomass at harvest (Donald and Hamblin, 1976; Hay, 1995).

*Yield components*

A few days before the crop harvest three final hand–harvested samples of ten plants randomly chosen were collected from each field to measure yield components. Number of pods in each plant were determined. To measure number of seed per pod, 50 pods were selected randomly and seeds were separated and counted using a seed counter (Contador, Pfeuffer). About 3000–5000 seeds were counted and weighed to determine 1000 seed weight.

*Seed quality*

Oil and protein content of the seed was determined using Infratec™ 1241 Grain Analyzer (Foss Tecator).

### *3.4 Input parameters and data needed by CROPGRO*

The CROPGRO model requires specific crop parameters as well as management, weather and soil data as input to run the model.

#### 3.4.1 Weather Data

Weather data were used for two station files creation named USOT (**U**niversity of **S**assari, **OT**tava site) and USON (**U**niversity of **S**assari, **O**tta**N**a site) using "Weatherman" program of DSSAT.

**Table 3.2** Information required by "Weatherman" program.

| Variables | Ottava (USOT) | Ottana (USON) |
|---|---|---|
| Latitude | 40° 46' 45.36'' N | 40° 14' 05.72'' N |
| Longitude | 8° 29' 35.14'' E | 9° 02' 38.58'' E |
| Elevation (m a.s.l) | 81 | 187 |
| Climate class | Mediterranean climate | Mediterranean climate |
| Tmax and Tmin (°C) | Daily weather data | Daily weather data |
| Precipitation (mm) | Daily weather data | Daily weather data |
| Solar radiation (MJ $m^2$ $s^{-1}$) | Daily weather data | Daily weather data |

#### 3.4.2 Soil Data

A US.sol and two profile files (USOT080001, **U**niversity of **S**assari, **OT**tava site, 20**08** growing season, profile number **0001** and USON080001, **U**niversity of **S**assari, **O**tta**N**a site, 20**08** growing season, profile number **0001**) were created using "Sbuild" program of DSSAT. This program requires information on soil surface, soil profile data, for each soil horizon in which roots are likely to grow and initial soil conditions.

The pedotransfer functions available in DSSAT (Tsuji *et al.*, 1994) were used to calculate some lacking soil surface and profile coefficients required to run the model as bulk density, wilting point, soil water content, field capacity and hydraulic conductivity.

**Table 3.3** Some of the variables required by "Sbuild" program.

| Variables | Ottava (USOT080001) | Ottana (USON080001) |
|---|---|---|
| Soil type | Sandy–clay loam | Sandy–clay loam |
| Sand (%) | 67.6 | 69.4 |
| Silt (%) | 11.4 | 7.6 |
| Clay (%) | 21.0 | 23.0 |
| pH ($H_2O$) | 8.33 | 6.29 |
| Organic C (%) | 1.22 | 1.16 |
| Total N (%) | 0.11 | 0.15 |

### 3.4.3 Crop Management Data

All data linked to crop management were used to create two files USOT0801 (**U**niversity of **S**assari, **OT**tava site, 20**08** growing season, experiment number **01**) and USON0801 (**U**niversity of **S**assari, **O**tta**N**a site, 20**08** growing season, experiment number **01**) by using "Xbuild" program of DSSAT. Variables required are listed below.

*Information required by "Xbuild" program*

1) Planting
   - Planting date
   - Row/Bed management (dimensions, mulch, dates)
     - Row spacing
     - Dimensions (bed width, depth of furrow)
     - Plastic mulch type, dates, dimensions
     - Number of rows per bed
     - Plant density along the rows

2) Crop description
   - Cultivar
   - Cultivar description (i.e., season length, pest resistance etc.)

3) Field management including provisions for fallow (weeds, residues left)
   - Irrigation system type (sprinkler, drip, furrow, subsurface)
     - Irrigation system parameters (i.e. water application rate per tree or furrow, emitter pattern, zone size, etc.)

- Dates and amounts of irrigation (or times irrigation system started and run time)

– Fertilizer application timing, amount, distribution, placement, and type

- Organic matter type and amount added, incorporation depth and %
  - %N, %C, and %P contents
  - % ground covered by organic matter
- Animal manure amount, type added, N and P content, incorporation depth and percentage. Ash, $NO_3$, $NH_4$ contents are also useful for manure
- Chemicals applied: dates, material applied, rate, and for what purposes
- For pastures, give management information such as stocking rate, animal body mass, and amount supplemental feed given per animal.

### 3.4.4 Experimental Data

Data collected during samplings were used for T (USOT0801.sbt and USON0801.sbt) and A (USOT0801.sba and USON0801.sba) crop measurement files creation, one for each site, using "ATCreate" program of DSSAT.

In particular, "ATCreate" program requires information on average performance for each treatment recorded during the course of growing season (T file) and at the end of season (A file).

## *3.5 Statistical analysis*

The goodness of fit of the model was assessed on the basis of both visual comparisons between simulated and field–measured values, and quantitative statistical measures, as recommended by Smith *et al*. (1996).

The statistical criteria we used to compare the time series of mean modeled and actual parameter considered (tops, pod, seed weight, LAI, SLA etc.) are the d–index coefficient, giving the association between the two series, and the Root Mean Square Error (RMSE). RMSE is here defined as: $RMSE=[\Sigma(O_i - P_i)^2/n]^{1/2}$, where $O_i$ and $P_i$ are the observed and predicted values, respectively, and *n* is the number of sampling dates.

# 4. RESULTS AND DISCUSSION

## *4.1 DSSAT parameter determination based on literature research*

### 4.1.1 Vegetative and reproductive development rates – Temperature

Several sources were used to document base and optimum range temperature for vegetative and reproductive development. Vigil *et al.* (1997) reported that base temperature was between 0.44 (summer rape) and 1.20 °C (winter rape) for emergence. Wilson *et al*. (1992) found no germination at 2 °C while Kondra *et al*. (1983) reported up to 91% germination of canola at 2 °C. Gabrielle *et al*. (1998a) in their study used a base temperature value of 4.5 °C close to the value of 5 °C found by Morrison *et al.* (1992) in their growth chamber environment experiment for germination to emergence. Mendham and Salisbury (1995) found that germination time varied between 1 to 14 days at 2 °C to 1 day at 21 to 25 °C while Copani *et al*. (1994), in their study in a Mediterranean environment, assumed a base temperature of 5 °C for germination and emergence. Data from Morrison *et al*. (1992) suggested that the optimum range of temperature for leaf development in summer rape was between 13 and 22 °C (17 °C mean temperature). As summarized in Table 4.1, base temperature of 5 °C and a first optimum temperature of 22 °C were used for both rate of emergence and rate of leaf appearance.

There is little data available on base and optimum range temperature for rate of progress to anthesis and to maturity although Robertson *et al.* (2002) reported a base and optimum temperature for reproductive development of 0 and 20 °C respectively.

A base temperature of 0 °C is proposed for early and late reproductive development (Table 4.1) because it is consistent with the vegetative processes and has been used by many researchers (Nanda *et al*., 1996; Kondra *et al.*, 1983). Following the optimum range of temperature given by Morrison *et al*. (1989), a first optimum temperature of 21 °C was used for progress to anthesis as well as progress during late reproductive development (beginning seed to maturity). Robertson *et al*. (1999) used Vigil's 1997 values for the calibration of their model and assumed an optimum temperature for progress to anthesis of 25 °C and an upper threshold of 35 °C. Polowick and Sawhney (1988) reported

that growth cabinet temperatures of 32/26 °C (day/night) resulted in sterile flowers with smaller sepals, petals and stamens while Morrison and Stewart (2002) in their field study found that the accumulation of daily temperature greater than 29.5 °C during the period from bolting to the end of flowering significantly reduced yield of *Brassica napus*.

Second optimum temperature of 25 °C and maximum temperature of 30 °C (Table 4.1) were selected for rate of progress from anthesis to maturity as well as progress during beginning seed maturity.

**Table 4.1** Species file: critical temperature for development of soybean and rapeseed as used in CROPGRO. Tb: base temperature, Topt1: first optimum, Topt2: second optimum, and Tmax: maximum.

| Crop | Developmental phase | Temperature | | | | Literature sources on rapeseed |
|---|---|---|---|---|---|---|
| | | Tb | Topt1 | Topt2 | Tmax | |
| Soybean | Vegetative | 7 | 28 | 35 | 45 | CROPGRO–Soybean model version 4.0.2; Wilkerson *et al.*, 1983 |
| | Early reproductive | 6 | 26 | 30 | 45 | CROPGRO–Soybean model version 4.0.2; Wilkerson *et al.*, 1983 |
| | Late reproductive | –15 | 26 | 34 | 45 | CROPGRO–Soybean model version 4.0.2; Wilkerson *et al.*, 1983 |
| Rapeseed | Vegetative | 5 | 22 | 25 | 30 | 5, 22 °C, Copani *et al.*, 1994; Morrison *et al.*, 1992 |
| | Early reproductive | 0 | 21 | 25 | 30 | 0, 21 °C Nanda *et al.*, 1996; Morrison *et al.*, 1989 |
| | Late reproductive | 0 | 21 | 25 | 30 | 25, 30 °C Robertson *et al.*, 1999; Morrison and Stewart, 2002 |

### 4.1.2 Reproductive development – Long day effect

Rapeseed is a quantitative long–day plant and there are several data documenting critical long daylength requirement or sensitivities to daylength change as those of King and Kondra (1986), Copani *et al*. (1994) and Nanda *et al*. (1996). Robertson *et al.* (2002) reported that days to flower decreased linearly as daylength was increased from 10.3 to 16.8 and Nanda *et al.* (1996) found that the greatest response occurred between 12 and 14 h. On average, a change in photoperiod from 12 to 14 h reduced the time to flowering by 40%. Several *Brassica napus* cultivar have been shown to flower earlier after exposure to

lower temperature. European winter cultivar required vernalization before flowering. Temperature of around 3 to 7 °C were found to be most effective for vernalization (Mendham and Salisbury, 1995). Robertson *et al*. (2002) found that vernalization response of *B. napus* saturated with 25 days at 3 °C and the base and optimum temperatures for development were confirmed at 0 and 20 °C respectively. Because the intermediate and early genotypes as Kabel (Salisbury and Green, 1991; Robertson *et al*., 2002) were least responsive to vernalization than vernalization was ignored and long–day effects (acceleration) up to anthesis was used.

The effect of long daylength was previously introduced into the CROPGRO model for the chickpea version (Hoogenboom, unpublished, 1998) and requires specifying a critical maximum long daylength, at which progress to anthesis is most rapid, plus a slope of daylength sensitivity that decreases rate of progress at shorter day lengths. A maximum long daylength of 16 h was assumed, based on results of Robertson *et al*. (2002). In addition to a critical maximum long day of 16 h, we used an apparent sensitivity of –0.0021 (PP–SEN) that defines the slope of cultivar sensitivity to long days (these are cultivar traits in Table 4.5).

Both Copani *et al.* (1994) and Nanda *et al.* (1996) suggested that rapeseed is accelerated toward anthesis by long days but that reproductive phases after anthesis are not sensitive to daylength. Indeed, Copani *et al.* (1994) mentioned a shortening of the reproductive phase from anthesis to maturity (in degree–days) with later sowing dates although this was attributed to water deficit.

### 4.1.3 Photosynthesis

CROPGRO has two options for predicting daily assimilate production: a daily canopy option and a hourly leaf–level option. The daily canopy option is the more simplistic approach, predicting photosynthate production as an asymptotic light response to total daily solar radiation levels. The leaf–level photosynthesis option predicts hourly photosynthetic rates for sunlit and shaded leaf area by simulating the dynamics of Rubisco activity and electron transport and integrates them within the hourly hedgerow approach to yield a daily canopy rate. Both options include adjustments for current temperature, $CO_2$ concentration, and leaf N concentration

conditions. The leaf–level photosynthesis option is a more complicated system requiring several more parameters than the daily canopy option, but the model at the leaf and chloroplast level incorporates several conserved processes for which parameters may be directly measured.

Light extinction coefficient for daily canopy option (KCAN) was set to 0.75 for rapeseed, as derived from Gosse *et al*. 1983 and Andersen *et al.* 1996. Leaf quantum efficiency (parameter name PGEFF) or quantum yield is broadly defined as the initial slope of the leaf $CO_2$ assimilation/absorbed PAR response. A value of 0.0560 μmol $CO_2$ $\mu mol^{-1}$ absorbed photons was reported in literature for *Brassica napus* (Farage and Long, 1991; Jensen *et al*., 1998) similar to 0.0541 μmol $CO_2$ $\mu mol^{-1}$ absorbed photons (Ehleringer and Björkman, 1977) typically used in CROPGRO for all C3 species, including soybean. Because there were no data on leaf photosynthesis, base and optimum temperature of leaf photosynthesis were approximated from those for emergence and rate of leaf appearance. Thus, a base temperature of 0 °C [FNPGT(1)], an optimum range of 17 °C and 25 °C [FNPGT(2), FNPGT(3)], and a maximum temperature (zero rate) of 35 °C [FNPGT(4)] were used for light–saturated leaf photosynthesis (Table 4.2). Light–saturated leaf photosynthesis has a more linear response to temperature because it depends mainly on electron transport rate. By contrast, quantum efficiency decreases as temperature increases. The resulting use of these two contrasting functions in the module of leaf–level canopy photosynthesis gives a very broad optimum temperature for canopy rate (Boote and Pickering, 1994).

Low temperature may also have a prolonged effect on photosynthesis, affecting photosynthetic rate after temperatures turned to the optimal range. CROPGRO uses another set of temperature, FNPGL(1–4) and TYPPGL, to describe the effect of minimum night temperature on the next day's light saturated leaf photosynthetic rate. Nanda *et al.* (1996) observed that in *Brassica napus* development is accelerated in relation to the reciprocal of the minimum night temperature above 2 °C. Based on this, we set the minimum temperature [no photosynthesis on the day after experiencing this temperature – FNPGL(1)] to –5 °C, optimum night temperature [no effect on next day's photosynthesis – FNPGL(2)] to 5 °C, with a quadratic response between these points. The model is quite sensitive to this parameter, especially during early to midseason when night temperatures were frequently less than

5 °C and the canopy was increasing in size. The respective base and optimum values are 4 and 22 °C for peanut, 0 and 19 °C for soybean, and 0 and 16 °C for dry bean. Thus, by comparison, rapeseed is presumed to be less affected by minimum temperature (night temperature) than these species.

The amount of photosynthetic enzymes in the leaf affect photosynthesis rate as well. Generally, higher N concentrations in the leaves are correlated with higher levels of these enzymes and higher photosynthetic capacity. Considering that the normal growth protein concentration of leaves tissue of rapeseed is likely to be lower than for soybean (0.188 vs 0.285, see Table 4.3) we obtained the two leftmost FNPGN(1–4) points for rapeseed scaled via soybean and set up to 1.3 [FNPGN(1)] and 4.0 [FNPGN(2)], that means that photosynthesis was set to be a quadratic function, increasing from zero at 1.3% N to maximum rate at 4.0% N. An optimum value of 35 g N $kg^{-1}$ leaf was then used for LNREF, the N concentration at which PGREF is defined for the species. By comparison, the function FNPGN(1–2) for soybean photosynthesis goes from 1.90 to 5.5% N and LNREF is equal to 49 g N $kg^{-1}$ leaf.

Habekotté (1997a) reported a maximum photosynthetic rate of individual leaves of 1.1111 mg $CO_2$ $m^{-2}$ $s^{-1}$ consistent with those found by Chongo and McVetty (2001) (0.88–1.14 mg $CO_2$ $m^{-2}$ $s^{-1}$) and by Hobbs (1988), who reported a mean of about 1.14 mg $CO_2$ $m^{-2}$ $s^{-1}$ in four oilseed rape cultivars. The CROPGRO model predicts gross canopy assimilation (before $CO_2$ losses from growth and maintenance respiration). During rapid growth, and using rapeseed composition, CROPGRO predicts that 32% of assimilates are concurrently respired for growth and maintenance respiration. Dividing Habekotté's (1997a) value of 1.1111 mg $CO_2$ $m^{-2}$ $s^{-1}$ by (1.000 – 0.32) gives us 1.63 mg $CO_2$ $m^{-2}$ $s^{-1}$ as the target rate of gross instantaneous canopy assimilation. This value is consistent with rates measured on soybean canopies (Boote *et al.*, 1984) where instantaneous crop dark respiration including roots and nodules was measured to be 30 to 40% of gross instantaneous assimilation. A midday canopy gross assimilation rate of 1.63 mg $CO_2$ $m^{-2}$ $s^{-1}$ requires that upper sunlit leaves have a light saturated rate between 1.0 to 1.2 mg $CO_2$ $m^{-2}$ $s^{-1}$ (Boote and Pickering, 1994). Using the CROPGRO model, predicted rates of gross canopy

assimilation were 1.8 mg $CO_2$ $m^{-2}$ $s^{-1}$ with input of leaf assimilation rate of 1.00 mg $CO_2$ $m^{-2}$ $s^{-1}$.

Maximum leaf photosynthetic rate (LFMAX) in Table 4.5 is defined at light saturation, 30 °C, 350 µL $L^{-1}$ $CO_2$, 21% $O_2$, and a reference specific leaf weight of 0.0075 g $cm^{-2}$. Relative differences among cultivars are modeled by changing the ratio of LFMAX (maximum leaf photosynthetic rate for the cultivar) to PGREF (maximum leaf photosynthetic rate for the species). As Kabel is the "reference" cultivar on which the species parameters are based, PGREF=LFMAX=1.000 mg $CO_2$ $m^{-2}$ $s^{-1}$.

**Table 4.2.** Rapeseed photosynthesis parameter values for the CROPGRO species file.

| Parameter Name | Soybean value | Rapeseed value |
|---|---|---|
| KCAN | 0.70 | 0.75 |
| FNPGN(1–4) | 1.9 5.5 20.0 20.0 | 1.3 4.0 20.0 20.0 |
| FNPGT(1–4) | 3.0 22.0 34.0 45.0 | 0.0 17.0 25.0 35.0 |
| XLMAXT(6) | 0.0 8.0 40.0 44.0 48.0 55.0 | 0.0 0.0 25.0 28.0 35.0 60.0 |
| FNPGL(4) | 0.0 19.0 50.0 60.0 | –5.0 5.0 25.0 30.0 |
| PGEFF | 0.0541 | 0.0560 |
| SLWREF | 0.0035 | 0.0075 |
| LNREF | 4.90 | 3.50 |
| PGREF | 1.000 | 1.000 |

### 4.1.4 Tissue composition, growth respiration, protein and carbohydrate mobilization

Composition of rapeseed seed (23.0% protein, 22.0% carbohydrate–cellulose, 48.0% lipid, 6.0% lignin, 1.0% ash and 1.0% organic acids) was based on values from Toniolo and Mosca (1986) and from Weiss (1983). The compositions for seed and vegetative tissues are specified in the species file, except for seed protein (SDPRO) and seed lipid (SDLIP), which are ecotype traits (Table 4.3). Internally, the CROPGRO model computes the growth respiration costs and conversion efficiencies for tissues based on these six approximate compositions, following the method of Penning De Vries and Van Laar (1982).

For leaves, stems, pod walls and roots, composition values were taken from cabbage, except for leaf protein concentration, for which rapeseed data were available from literature (Triboi–Bondel, 1988). CROPGRO requires three values for protein composition of leaves and other tissues: the luxury consumption value (maximum value under high N fertilization), the typical value, and the minimum concentration at which all available protein is exhausted at leaf senescence and photosynthesis is nearly zero. Based on different references (Triboi–Bondel, 1988; Malagoli *et al.*, 2005) we set the luxury value at 6.0% (0.375 protein), the typical leaf N concentration at 3.0% (0.188 protein), and the minimum N at 2.0% (0.125 protein). One reference (Malagoli *et al.*, 2005) listed deficient N concentration as varying from 1.8 to 2.5%; thus, the minimum N concentration was set at 2.0% based on soybean as soybean leaves have similar luxury N values as rapeseed.

**Table 4.3.** Species file: tissue composition (concentrations as g $g^{-1}$ tissue dry weight) of soybean and rapeseed as used in CROPGRO.

| Compounds | Tissue | CROPGRO coefficient | Soybean | Rapeseed | Literature sources |
|---|---|---|---|---|---|
| Proteins | Leaf | PROLFG | 0.285 | 0.188 | Triboi–Bondel, 1988 |
| | Stem | PROSTG | 0.110 | 0.110 | Same as cabbage |
| | Root | PRORTG | 0.064 | 0.076 | Same as cabbage |
| | Shell | PROSHG | 0.196 | 0.150 | Same as cabbage |
| | Seed | SDPROG | 0.400 | 0.230 | Toniolo and Mosca, 1986 |
| Lipids | Leaf | PLIPLF | 0.025 | 0 024 | Same as cabbage |
| | Stem | PLIPST | 0.020 | 0.017 | Same as cabbage |
| | Root | PLIPRT | 0.020 | 0.024 | Same as cabbage |
| | Shell | PLIPSH | 0.020 | 0.024 | Same as cabbage |
| | Seed | PLIPSD | 0.200 | 0.480 | Toniolo and Mosca, 1986 |
| Carbohydrates | Leaf | PCARLF | 0.405 | 0.516 | Same as cabbage |
| | Stem | PCARST | 0.649 | 0.675 | Same as cabbage |
| | Root | PCARRT | 0.711 | 0.694 | Same as cabbage |
| | Shell | PCARSH | 0.380 | 0.626 | Same as cabbage |
| | Seed | PCARSD | 0.315 | 0.220 | Toniolo and Mosca, 1986 |
| Lignins | Leaf | PLIGLF | 0.070 | 0.111 | Same as cabbage |
| | Stem | PLIGST | 0.070 | 0.076 | Same as cabbage |
| | Root | PLIGRT | 0.280 | 0.111 | Same as cabbage |
| | Shell | PLIGSH | 0.028 | 0.111 | Same as cabbage |
| | Seed | PLIGSD | 0.020 | 0.060 | Toniolo and Mosca, 1986 |
| Minerals | Leaf | PMINLF | 0.094 | 0.043 | Same as cabbage |
| | Stem | PMINST | 0.046 | 0.030 | Same as cabbage |
| | Root | PMINRT | 0.057 | 0.043 | Same as cabbage |
| | Mineral shell | PMINSH | 0.030 | 0.043 | Same as cabbage |
| | Mineral seed | PMINSD | 0.025 | 0.010 | Toniolo and Mosca, 1986 |

CROPGRO allows protein mobilization from vegetative tissues, during vegetative growth. This function (NVSMOB) was increased to 0.40 compared with soybean (0.35) to allow mobilizing of most of the available protein from the leaves soon after peak of flowering when pods begin development. Coefficients for carbohydrate storage and mobilization in vegetative tissues were accepted from the soybean species file and found to response satisfactorily. These coefficients create a given level of available carbohydrate in newly produced vegetative tissue, allow carbohydrate to accumulate during periods of N deficit, provide for carbohydrate storage in stems and leaves upon the transition from anthesis until setting a full seed load, and allow subsequent mobilization of carbohydrates for growth.

### 4.1.5 Vegetative expansion processes

In CROPGRO, two factors affect the time to end of leaf area expansion: first, there is a photothermal time after anthesis (FL–LF) during which expansion can continue, and second, within that phase, leaf area expansion continues as long as assimilate is partitioned to leaves (terminates naturally when all assimilate is going to reproductive organs). To check timing of LAI peak, FL–VS (Table 4.4) was set to 0 photothermal days after first flower, thus allowing stopped development of leaves on the main stem. Similarly, FL–LF was set to allow leaf area expansion until 1 photothermal days after first flower.

**Table 4.4.** Rapeseed photosynthesis parameter values for the CROPGRO species and ecotype file.

| Parameter name | File type | Soybean value | Rapeseed value |
|---|---|---|---|
| FL–VS | ECO | 9.00 | 0.00 |
| XSLATM(1–5) | SPE | –50.0 00.0 12.0 22.0 60.0 | –50.0 00.0 6.0 15.0 60.0 |
| XHWTEM(1–5) | SPE | –50.0 00.0 15.0 26.0 60.0 | –50.0 0.0 4.5 14.5 60.0 |
| TURFAC | SPE | 0.00 0.50 0.75 1.00 | 0.00 0.50 0.75 1.00 |
| TRIFL | ECO | 0.32 | 0.35 |

CROPGRO has several ancillary functions by which temperature, light, and water affect leaf area expansion, canopy height, and canopy width. A primary effect of temperature already discussed is on rate of leaf appearance (Table 4.4). Temperature, light, and water deficit have additional effects on

leaf area expansion and internode elongation per se, resulting in altered specific leaf area (SLA), canopy height, and canopy width. The temperature function affecting SLA is assumed to have a base temperature of 4.5 °C [XSLATM(3)], when expansion is 0.80 of optimum, and an optimum temperature [XSLATM(4)] of 15 °C when expansion occurs at the optimum rate (Table 4.4). Temperature sensitivity of internode elongation assumes base temperature of 4.5 °C [XHWTEM(3)] and optimum temperature of 14.5 °C [XHWTEM(4)], giving 0.80 of normal internode length at 4.5 °C and linearly increasing to 1.0 of normal internode length at 14.5 °C (Table 4.4). There is no evidence supporting these values, other than base temperature of 5 °C being used for related processes such as rate of node appearance.

CROPGRO includes a light history effect, whereby increasing light causes decreased internode length and lower SLA. In addition, CROPGRO computes a turgor factor (TURFAC), which can decrease internode elongation and the SLA of today's leaf growth. The latter two features were unchanged from soybean coefficients. Crop height and width are predicted by CROPGRO as a function of increase in main–stem node number and of successive internode length. Vegetative node number over time was reasonably well predicted (data not shown), using 0.35 nodes $PD^{-1}$, a base temperature of 5 °C and optimum temperature of 22 °C. CROPGRO's species file has a lookup array that defines maximum potential internode length for successive nodes above the cotyledonary node. In this case, due to the lack of literature sources, we used soybean's values. Like soybean, early internodes are shorter, and successive nodes become longer until about two–thirds of the final node number are expressed. In addition, internodes are predicted to be shorter as a function of water deficit and cool temperature. With these calibrations, we were able to reasonably predict canopy height over time. Canopy height was derived from literature sources (De Mastro, 1998; De Mastro *et al.*, 2000) and set to 1.5 m (Ecotype traits).

### 4.1.6 Pod addition, seed addition and seed growth

The CROPGRO model begins to add pods at the beginning pod stage (which occurs at FL–SH PD after anthesis, Table 4.5). Pods are added for a photothermal dependent duration (PODUR, Table 4.5) at a rate that depends on

current canopy assimilation rate and current temperature. After a given duration (FL–SD, a cultivar dependent number of PD after anthesis, Table 4.5), seeds are added in the cohorts as they reach appropriate pod age defined by FL–SD minus FL–SH. There were no data on base temperature and optimum temperature range for pod addition and seed addition; therefore, we set temperature effects on rapeseed by analogy to soybean values. For example, soybean has base temperature, optimum temperature range and maximum temperature of 14, 21, 26.5 and 40 °C, respectively, for pod addition. Soybean is reported to have temperature sensitivity that limits pod addition at temperatures well above the base temperature of 7 °C used for vegetative growth. Rapeseed is less sensitive to cold and we used base temperature, optimum range temperature and maximum temperature of 0, 9.5, 20.3 and 29.8 °C [FNPDT(1–4)], respectively, for pod addition. Seed growth rate has a different function, again set for rapeseed by analogy to soybean values. Soybean uses base temperature, optimum range temperature, and maximum temperature of 6, 21, 23.5, and 41 °C, respectively, set from data of Egli and Wardlaw (1980). For single–seed growth rate of rapeseed, we set base temperature, optimum range temperature, and maximum temperature to 0, 14.5, 24.5, and 35.5 °C [FNSDT(1–4)], respectively, close to reported temperature coefficients for vegetative and reproductive development of rapeseed.

### 4.1.7 Cultivar values

The CROPGRO model uses cultivar and ecotype files to quantify how cultivars and major groups of cultivars differ with respect to durations of the life cycle phases, daylength sensitivities, number of seeds per pod, seed size, determinacy of both pod addition and leaf area growth, SLA, leaf photosynthesis rate, relative internode length, and canopy width etc. (Table 4.5).

In this approach, the CROPGRO model was run with weather data and degree–days were computed as defined by French and German scientists and at the same time, translated to PD. In this way, PD were derived from the following reported degree–day values: time to emergence (120 °C–d, from Gabrielle *et al.*, 1998a), time to flowering (576–606 °C–d from Morrison and Stewart, 2002), and time from flowering to maturity (1060 °C–d, from Nanda *et al.*, 1996) and our computed values for the cultivar Kabel in our study were

between 1030 (Ottana site) and 1165 °C–d (Ottava site) for the whole cycle. Likewise, we derived PD durations for time from anthesis to beginning pod (240–320 °C–d), time from anthesis to rapid seed growth (410–450 °C–d), and duration of flowering and pod addition (PODUR) (130–180 °C–d).

**Table 4.5.** Cultivar genetic coefficients of rapeseed for the CROPGRO model, after the calibration process based on literature research.

| Genetic coefficients | Rapeseed |
|---|---|
| Critical short daylength above which reproductive development progresses with no daylength effect (CSDL) (h) | 16.00 |
| Slope of the relative response of development vs photoperiod (PP–SEN) (1/h) | –.0021 |
| Time between emergence and flower appearance (EM–FL) (PD) | 35.0 |
| Time between first flower and beginning pod (FL–SH) (PD) | 9.0 |
| Time between first flower and beginning seed (FL–SD) (PD) | 25.0 |
| Time between beginning seed and physiological maturity (SD–PM) (PD) | 33.6 |
| Time between beginning seed and end of leaf expansion (FL–LF) (PD) | 1.0 |
| Maximum leaf photosynthetic rate at 30 °C, 350 vpm $CO_2$, and high light (LFMAX) (mg $CO_2$ $m^{-2}$ $s^{-1}$) | 1.000 |
| Specific leaf area of cultivar under standard growth conditions (SLAVR) ($cm^2$ $g^{-1}$) | 225 |
| Maximum size of full leaf (SIZLF) ($cm^2$) | 95 |
| Maximum fraction of daily growth that is partitioned to seed + shell (XFRT) | 1.00 |
| Maximum weight per seed (WTPSD) (g) | 0.0034 |
| Seed–filling duration for pod cohort under standard conditions (SFDUR) (PD) | 23.0 |
| Seeds per pod at standard growth conditions (SDPDV) (no. $pod^{-1}$) | 22 |
| Duration of pod addition under standard conditions (PODUR) (PD) | 7.5 |

The parameter SIZLF was calibrated with the aim to consider the effects of full sun conditions on leaf area/size development by plants. However, leaf area of rapeseed can vary with node position at optimal conditions between 7.0 and 94.7 $cm^2$ (Triboi–Bondel, 1988). SIZLF for full sun conditions was estimated to be 95 $cm^2$ (Table 4.5) based on the much larger leaf size that rapeseed obtained in our trials. SLAVAR value (Table 4.5) in the calibration was 225 $cm^2$ $g^{-1}$, lower than the default model value in order to fit for the relatively lower area–weight ratio of rapeseed leaves for this variety and consistent with values reported in the literature for other varieties (Liu *et al*., 2009).

Initially, maximum weight per seed (3.4 mg) was derived from literature (De Mastro, 1998; De Mastro *et al.*, 2000) while number of seeds per pod was set to 22 (SDPDV) and was found to be in the range with values reported in the literature for other cultivars (Fortescue and Turner, 2007). These cultivar thresholds were set initially from literature reports on other cultivars and subsequently evaluated to see if they worked satisfactory for the Kabel cultivar in our study.

## 4.2 Model adaptation based on growth analysis

Additional model adaptation for rapeseed was focused on changes to improve simulations by comparison to observed growth, development, dry matter accumulation and partitioning of the Kabel cultivar grown in our study. Results in figures and tables show simulations after final adaptations and are not intended as a validation statement. In the prior section, species file aspects presumed to be generic for rapeseed were taken from literature, but these came from many different cultivars. Thus, it is not surprising that the comparison to observed data for the Kabel cultivar required not only minor changes to the species files, but also setting of the cultivar–ecotype file parameters for this cultivar.

### 4.2.1 Crop cycle

Using a critical short daylength of 16 h with a PP-SEN of –0.021 did not predict flowering adequately to the data of the cultivar used.

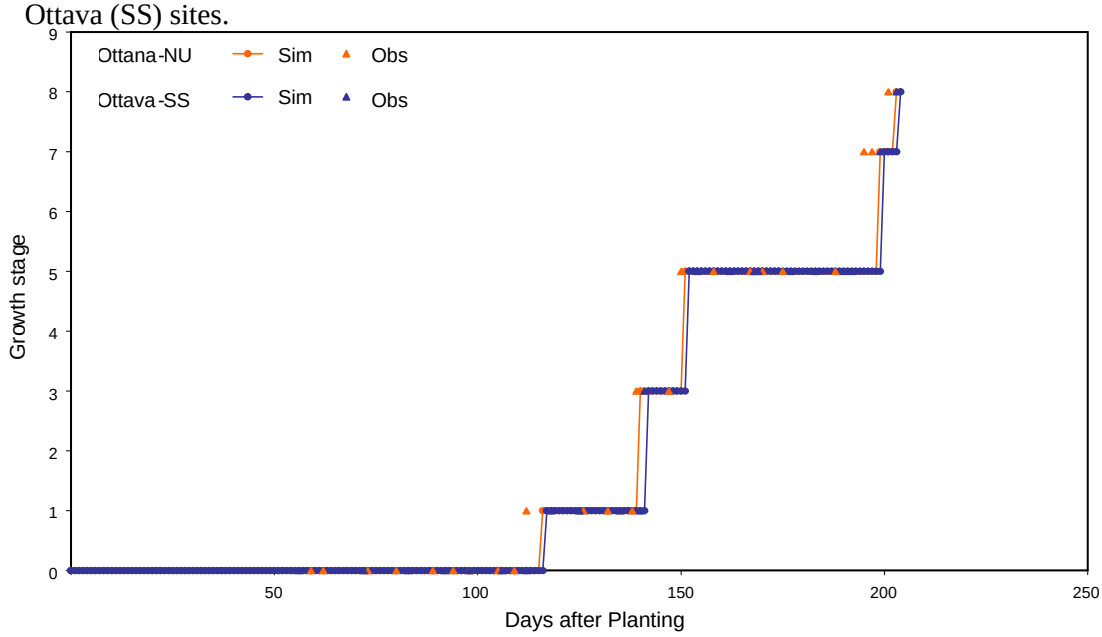
Assuming that, in 2009 growing season, rapeseed progressed to flowering without any photoperiod effect because of delay in sowing we had been able to compute the correct number of PD need from emergence to anthesis (EM–FL) and as consequence a slope of –0.006 was calibrated to simulate the daylength sensitivity of rapeseed. Setting the PP–SEN to –0.006 improved prediction of flowering, and this value was maintained in subsequent simulations.

Flowering date in 2008 were predicted with a RMSE of 2.91 days across locations. Observed flowering date ranged from 112 to 118 days after planting (dap) and simulated values from 116 to 118.

**Table 4.6.** Comparison of observed and simulated life cycle variables averaged over Ottana and Ottava sites data, the root mean square error (RMSE) and d-index.

| Variable | Simulated mean | Observed mean | RMSE | d-stat |
|---|---|---|---|---|
| Anthesis day (dap) | 117 | 115 | 2.91 | 0.58 |
| First pod day (dap) | 141 | 140 | 1.00 | 0.80 |
| First seed day (dap) | 152 | 152 | 1.58 | 0.62 |
| Physiological maturity day (dap) | 200 | 197 | 2.91 | 0.58 |
| Harvest maturity day (dap) | 203 | 202 | 0.71 | 0.80 |

**Figure 4.1.** A comparison of simulated (lines) and observed (symbols) growth stage as a function of days after sowing for rapeseed cultivar Kabel grown in Ottana (NU) and in Ottava (SS) sites.




Time from anthesis to beginning pod (FL–SH) and time from anthesis to beginning seed (FL–SD) had only been previously set both from literature on other cultivars and from our trials observed data. Thus, initially, the timing of pod growth was early by a few days, despite correct prediction of anthesis date for the Kabel cultivar. As a result, we modified three coefficients for the Kabel cultivar (increased FL–SH from 9 to 12.5 days and decreased FL–SD from 25 to 18.5 days and time between beginning seed and physiological maturity from 33.6 to 33.5 days, Table 4.7) to delay the onset of rapid pod growth but

maintain the same total life cycle. This shift resulted in the correct initial increase in pod mass.

**Table 4.7.** Genetic coefficients of cultivar Kabel for the CROPGRO model, after the calibration process based on trials data.

| Genetic coefficients | Kabel |
|---|---|
| Critical short daylength above which reproductive development progresses with no daylength effect (CSDL) (h) | 16.00 |
| Slope of the relative response of development vs photoperiod (PP–SEN) (1/h) | –.0006 |
| Time between emergence and flower appearance (EM–FL) (PD) | 45.0 |
| Time between first flower and beginning pod (FL–SH) (PD) | 12.5 |
| Time between first flower and beginning seed (FL–SD) (PD) | 18.5 |
| Time between beginning seed and physiological maturity (SD–PM) (PD) | 33.5 |
| Time between beginning seed and end of leaf expansion (FL–LF) (PD) | 1.0 |
| Maximum leaf photosynthetic rate at 30 °C, 350 vpm $CO_2$, and high light (LFMAX) (mg $CO_2$ $m^{-2}$ $s^{-1}$) | 1.000 |
| Specific leaf area of cultivar under standard growth conditions (SLAVR) ($cm^2$ $g^{-1}$) | 225 |
| Maximum size of full leaf (SIZLF) ($cm^2$) | 95 |
| Maximum fraction of daily growth that is partitioned to seed + shell (XFRT) | 1.00 |
| Maximum weight per seed (WTPSD) (g) | 0.0030 |
| Seed–filling duration for pod cohort under standard conditions (SFDUR) (PD) | 20.0 |
| Seeds per pod at standard growth conditions (SDPDV) (no. $pod^{-1}$) | 18 |
| Duration of pod addition under standard conditions (PODUR) (PD) | 10.0 |

Testing of the preliminary, trials-based, genetic coefficients was encouraging with d-index values of 0.80, 0.62 and 0.80 for time to first pod, time to first seed and harvest dates, respectively.

In general, the root mean square error and d–index for the whole crop cycle were 0.90 day and 0.95, respectively.

### 4.2.2 Biomass and pod mass accumulation

After calibrating anthesis and maturity parameters as above and setting species parameters and relationships to the extent possible based on independent literature, we compared simulated growth of rapeseed with

observed crop biomass and pod mass of Ottana and Ottava sites, both during the season (Figure 4.2) and at final harvest (Table 4.8).

Only final simulations are shown in the figures and Table 4.8, because our objective was to calibrate and adapt a new model for a first comparison. Table 4.8 illustrates model predictions, root mean square errors and d-index for crop variables measured at final harvest and averaged over Ottana and Ottava sites during 2008 growing season.

**Table 4.8.** Comparison of observed and simulated crop variables at maturity averaged over Ottana (NU) and Ottava (SS) sites data, the root mean square error (RMSE) and d-index.

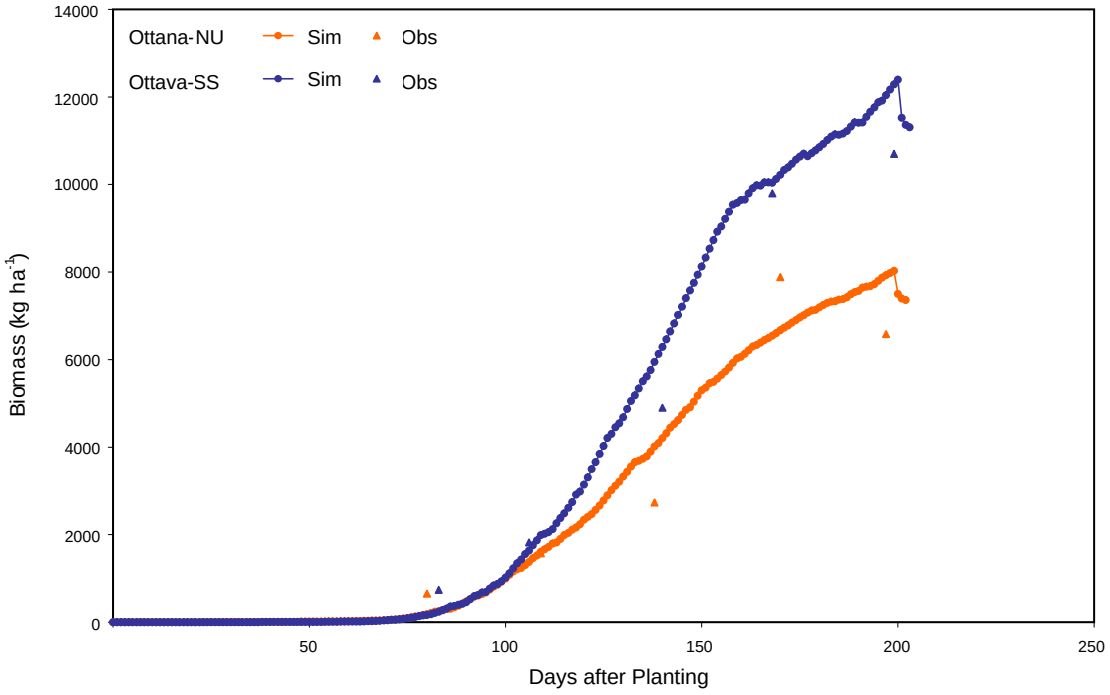
| Variable | Simulated mean | Observed mean | RMSE | d-stat |
|---|---|---|---|---|
| Crop mass (kg $ha^{-1}$) | 9126 | 8642 | 487.3 | 0.99 |
| Seed yield (kg $ha^{-1}$) | 3174 | 3270 | 110.5 | 1.00 |
| Seed number (no $pod^{-1}$) | 18 | 18 | 0.71 | 0.50 |
| Seed number (no $m^{-2}$) | 112250 | 115495 | 3244.6 | 1.00 |
| Unit seed weight (mg) | 3.00 | 3.00 | 0.00 | 1.00 |
| Seed Harvest Index | 0.35 | 0.38 | 0.003 | 0.00 |
| Seed N (%) | 3.10 | 3.22 | 0.14 | 0.62 |
| Seed oil (%) | 43.8 | 44.4 | 1.65 | 0.12 |

Final comparisons showed correct prediction of slope of dry matter accumulation with a RMSE and d–index of 886.0 kg $ha^{-1}$ and 0.99, respectively (Figure 4.2) for Ottava site, while a slight underprediction of slope of dry matter accumulation (RMSE 979.1 kg $ha^{-1}$, d–index 0.97) but correct prediction of final biomass for Ottana site (last sample dates in Figure 4.2 and Table 4.8). Final comparisons showed correct prediction of slope and a significant overprediction of pod mass accumulation for Ottava site with a RMSE of 1794 kg $ha^{-1}$ and d–index of 0.75, while for Ottana site the model underestimated final pod mass accumulation (RMSE of 1517 kg $ha^{-1}$ and d–index of 0.77).

Only minor modifications were needed for the canopy photosynthesis functions. Indeed, the maximum leaf photosynthetic rate (LFMAX) was unchanged and comparable to soybean while changes were made primarily to

functions affecting early season assimilation when the canopy was small and temperatures were cool. These were related to Tmin effect on photosynthesis and also attributed to incorrect partitioning to leaf and stem, which was resolved by calibration of partitioning as described later.

**Figure 4.2.** A comparison of simulated (lines) and observed (symbols) crop biomass as a function of days after sowing for rapeseed cultivar Kabel grown in Ottana (NU) and in Ottava (SS) sites.

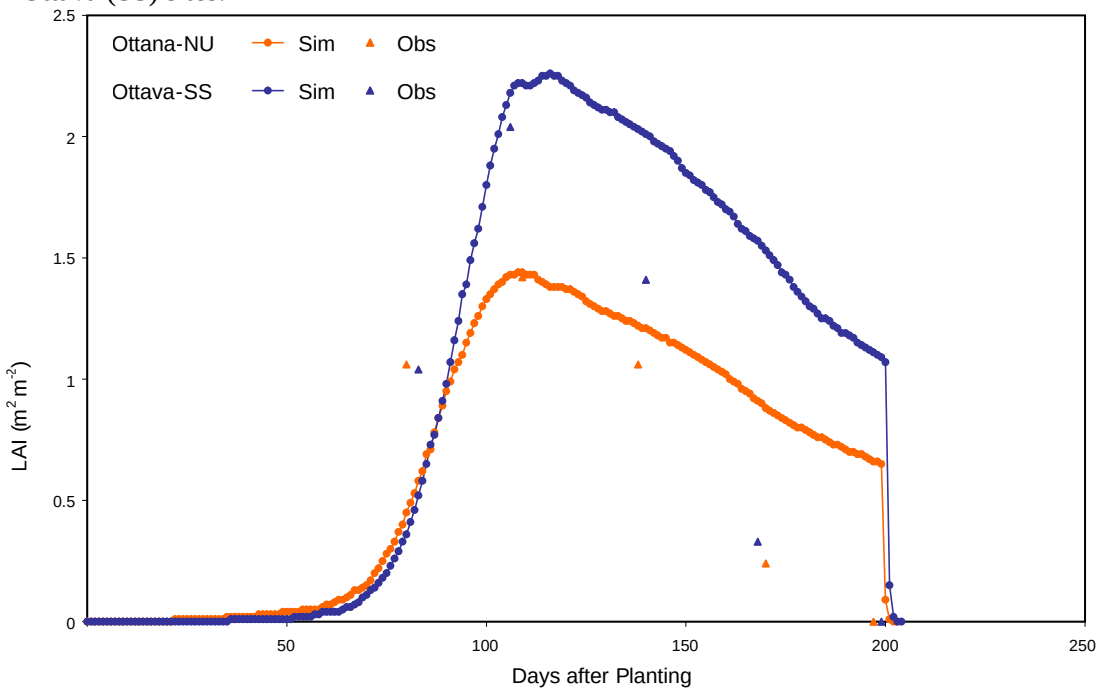



### 4.2.3 Leaf Area Index and Specific Leaf Area

The model's ability to predict LAI (Figure 4.3) depends on the ability to predict leaf mass (from daily growth and current partitioning to leaf) and SLA. Dry matter allocation to leaf mass is determined by the partitioning function modified for rapeseed as described later. The SLA of new leaves depends on environment: solar irradiance, temperature (decreased if cool) and water deficit (decreased when TURFAC is less than 1.0). For the response to light, two parameters (SLAMAX and SLAMIN) determine SLA of new leaves within potential SLA limits under low or high irradiance, respectively. These two parameters were calibrated and set at 660 and 99.5 $cm^2$ $g^{-1}$. The SLAMIN parameter basically sets the potential SLA of the species during the peak canopy LAI phase. Simulated SLA can be less than SLAMIN if there are water deficit or temperature limitations or higher if irradiance is low. The time of maximum LAI in the model is influenced by the onset of pod and seed growth,

partitioning between vegetative components (leaf, stem and root) and the time when leaf area expansion ceases. The latter is set by the variable FL–LF (Table 4.7), which is the PD from anthesis to end of leaf area expansion, after which any leaf mass added has SLA of zero. The FL–LF was set to 1 PD. Secondary thickening is possible if assimilate is available after FL–LF. Based on our visual inspection of the Kabel cultivar, there were no immature or unexpanded leaves remaining when rapid seed growth had begun.

**Figure 4.3.** A comparison of simulated (lines) and observed (symbols) Leaf Area Index as a function of days after sowing for rapeseed cultivar Kabel grown in Ottana (NU) and Ottava (SS) sites.




The experimental fit of the Ottana and Ottava simulations in Figure 4.3 was satisfactory, with RMSE in the range 0.43–0.73 $m^2$ $m^{-2}$ and d–index ranging from 0.63–0.68. The timing and the time of maximum LAI (Table 4.9) before the decline associated with the onset of pod growth was well simulated. Simulated LAI reached a peak of 1.40 and 2.28 $m^2$ $m^{-2}$ in Ottava and Ottana, respectively, close to observed LAI peak data (1.42 and 2.04 $m^2$ $m^{-2}$). However, the model failed to accurately predict the rate of LAI decrease after flowering (time of LAI peak). From DAS 116 to DAS 199 for Ottana and from DAS 117 to 200 for Ottava, leaf senescence seems to have been underestimated by the model, yielding values of green LAI higher than observed.

Fit of predicted SLA (Figure 4.4) was not as good as was LAI, in particular it was consistently overpredicted for the Ottana site (RMSE 113.7 $cm^2$ $g^{-1}$ and Wilmott's coefficient 0.60) while in Ottava site simulation of SLA was good with a RMSE of 59.7 $cm^2$ $g^{-1}$ and d-index of 0.70.

**Figure 4.4.** A comparison of simulated (lines) and observed (symbols) Specific Leaf Area as a function of days after sowing for rapeseed cultivar Kabel grown in Ottana (NU) and Ottava (SS) sites.

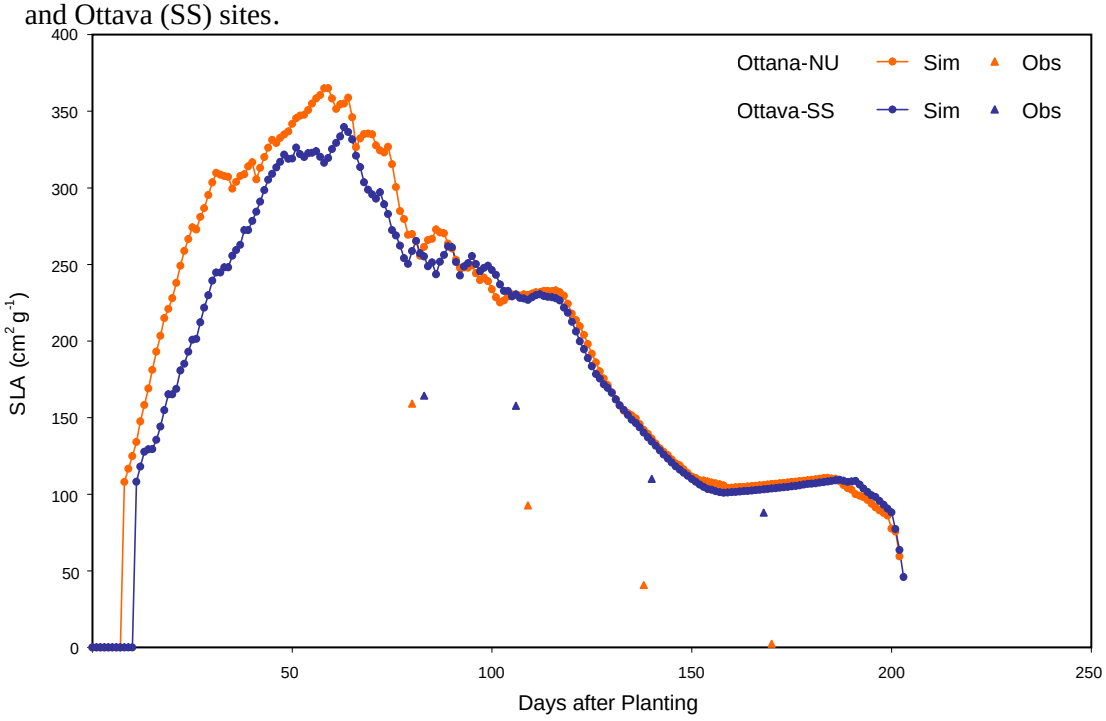



**Table 4.9.** Comparison of observed and simulated LAI and SLA averaged over Ottana and Ottava sites data and the root mean square error (RMSE) and d-index.

| Variable | Simulated mean | Observed mean | RMSE | d-stat |
|---|---|---|---|---|
| Leaf Area Index (LAI) | 1.26 | 1.07 | 0.58 | 0.65 |
| Leaf Area Index maximum | 1.83 | 1.73 | 0.17 | 0.95 |
| Specific Leaf Area (SLA) | 183.4 | 101.9 | 86.69 | 0.65 |

### 4.2.4 Partitioning of dry matter to pod, leaf, stem and root

The species file contains an array function that describes the instantaneous daily partitioning among leaf, stem and root tissues, depending on crop developmental stage (vegetative and reproductive), until addition and growth of pods and seeds become dominant in assimilate demand. Partitioning of dry matter among aboveground tissues was evaluated by comparing simulated vs observed fraction leaf, fraction stem and pod, which are the

cumulative result of daily partitioning among aboveground tissues. The original instantaneous daily partitioning function from soybean was inadequate for rapeseed and the function was modified to better predict cumulative fractions of dry matter found in leaf and stem. We did not have observed values for fraction root but compared with values published by Tayo and Morgan (1975), who reported that apparent fraction root decreased initially from 0.60 to 0.10 by the time of rapid pod growth when root growth was essentially complete. Model predictions of apparent fraction root after calibration mostly mimic the decline in fraction root that they reported, as would be generated by model use of the instantaneous daily partitioning function.

**Table 4.10.** Vegetative partitioning parameters of rapeseed species for the CROPGRO model after the calibration process.

| Variable | Soybean value | Rapeseed value |
|---|---|---|
| XLEAF | 0.0 1.5 3.3 5.0 7.8 10.5 30.0 40.0 | 0.0 6.3 7.4 7.5 8.6 09.0 10.0 15.0 |
| YLEAF | 0.41 0.42 0.42 0.41 0.36 0.32 0.31 0.31 | 0.80 0.80 0.68 0.56 0.16 0.10 0.04 0.03 |
| YSTEM | 0.09 0.13 0.21 0.29 0.37 0.49 0.49 0.49 | 0.01 0.01 0.20 0.29 0.65 0.67 0.71 0.76 |
| PORPT, FRSTMF | 0.58 0.55 | 0.15 0.72 |

Compared with soybean (initial default), the partitioning to leaf early in the life cycle had to be increased while partitioning to stem was decreased. During mid– to late life cycle, partitioning to stem was increased and partitioning to leaf was decreased (Table 4.10). The onset of pod and seed addition decreases the actual partitioning to vegetative components and thus affects the amount of stem mass produced during mid–life cycle before rapid pod growth and influences the apparent fraction stem and leaf. In addition, the partitioning to leaf during early season was somewhat interactive with SLA, LAI and a model feature that sets an upper limit on early leaf area expansion for the first five nodal positions as a function of vegetative stage.

### 4.2.5 Yield components

Measured and simulated yield components are presented in Table 4.8. The final mass per seed at harvest depends on genetic potential seed size (WTPSD) and environmental conditions during seed growth. The average unit seeds

harvested weights were lower than 0.0034 g, initially set from literature in cultivar file, possibly due to slight nitrogen and water stress at the Ottana and Ottava sites. Modeled seed size was calibrated to observed by setting WTPSD to 0.0030 g per seed. Figure 4.5 shows unit seed weight development in Ottana and Ottava sites.

The average seed number per pod (SDPDV) was slightly lower in comparison to what reported in literature for Kabel cultivar. The average seed number per pod was changed in the cultivar file to 18. Maximum threshing percentage at maturity (THRESH, seed divided by pod wall plus seed) was changed from 78% (soybean value) to 81% to account for the thinner pod walls (shells) observed in our trials.

After model calibration based on observed data, the predictions of unit seed weight and grain yield (Figures 4.5-4.6) were good both for Ottana and Ottava site.

**Figure 4.5.** A comparison of simulated (lines) and observed (symbols) unit seed weight as a function of days after sowing for rapeseed cultivar Kabel grown in Ottana (NU) and Ottava (SS) sites.

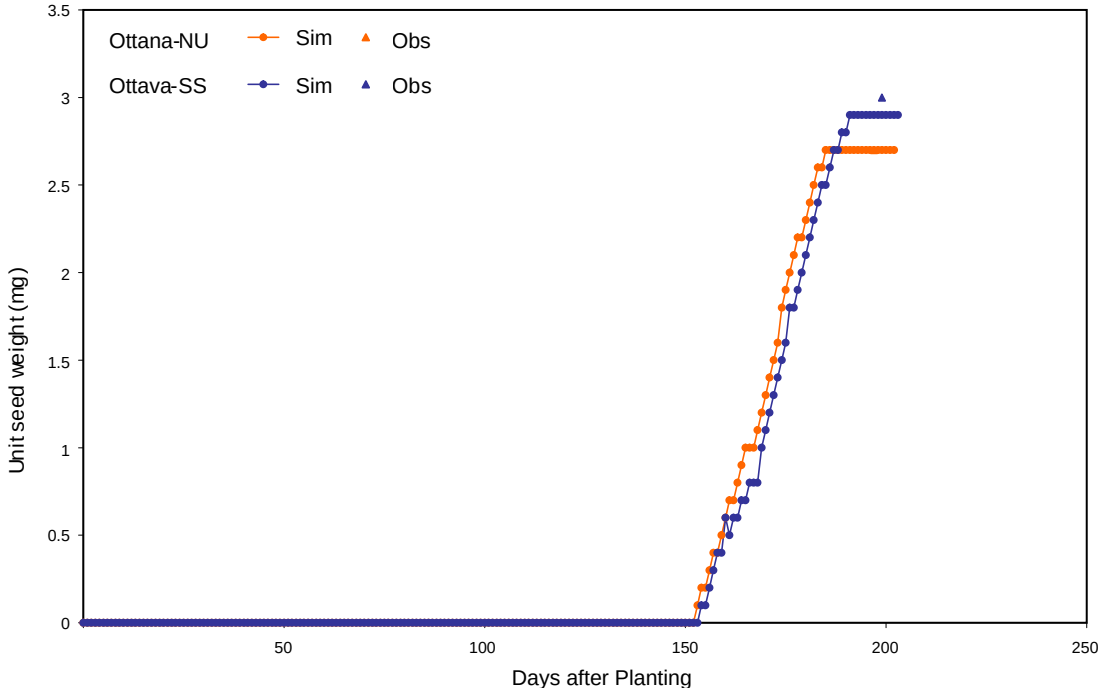


**Figure 4.6.** A comparison of simulated (lines) and observed (symbols) seed yield as a function of days after sowing for rapeseed cultivar Kabel grown in Ottana (NU) and Ottava (SS) sites.

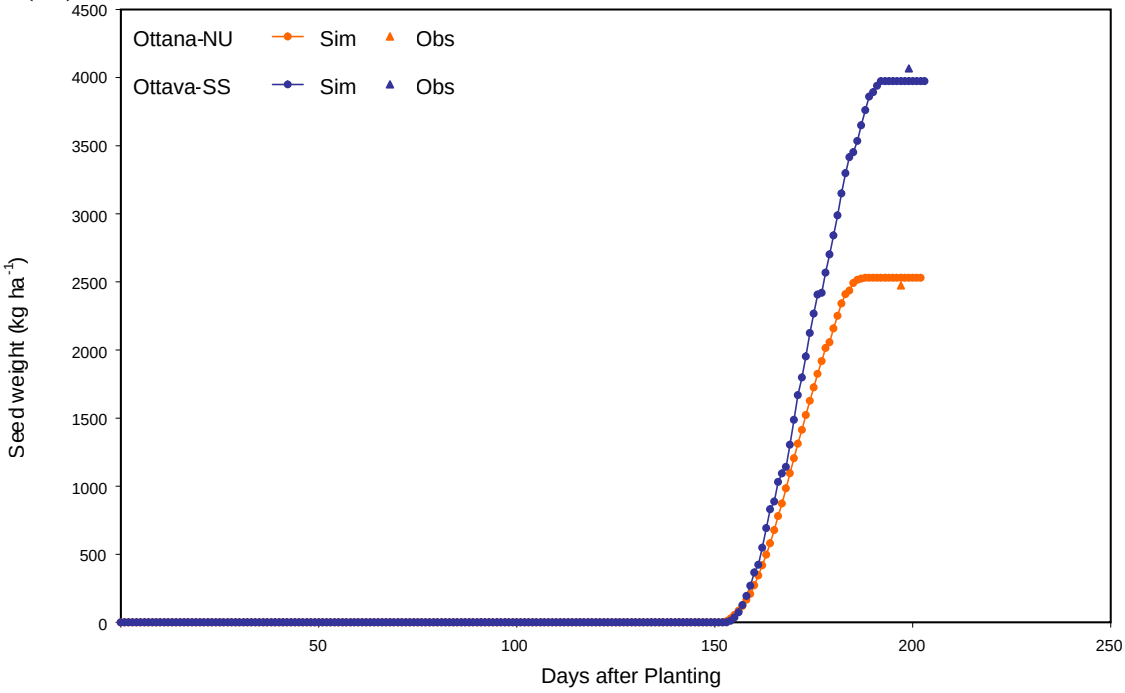
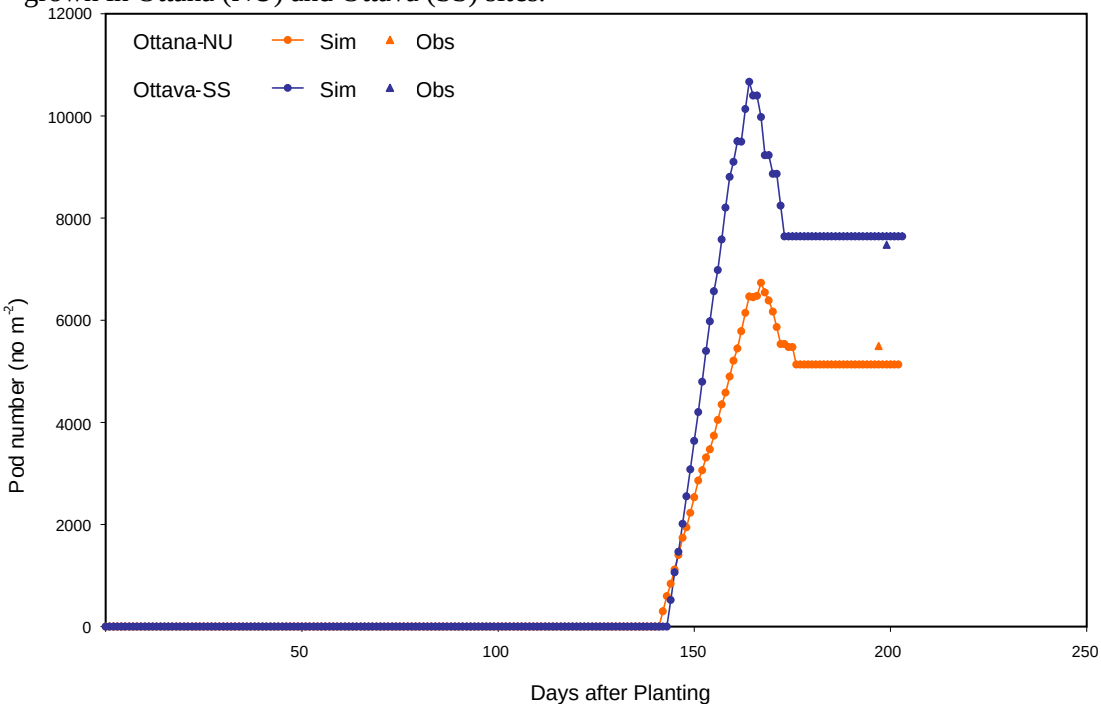



**Figure 4.7.** A comparison of simulated (lines) and observed (symbols) number of pod per square meter at maturity as a function of days after sowing for rapeseed cultivar Kabel grown in Ottana (NU) and Ottava (SS) sites.




Calibration with observed data improved the predicted number of pod and number of seed per square meter too (Table 4.8 and Figures 4.7-4.8).

**Figure 4.8.** A comparison of simulated (lines) and observed (symbols) number of seed per square meter at maturity as a function of days after sowing for rapeseed cultivar Kabel grown in Ottana (NU) and Ottava (SS) sites.

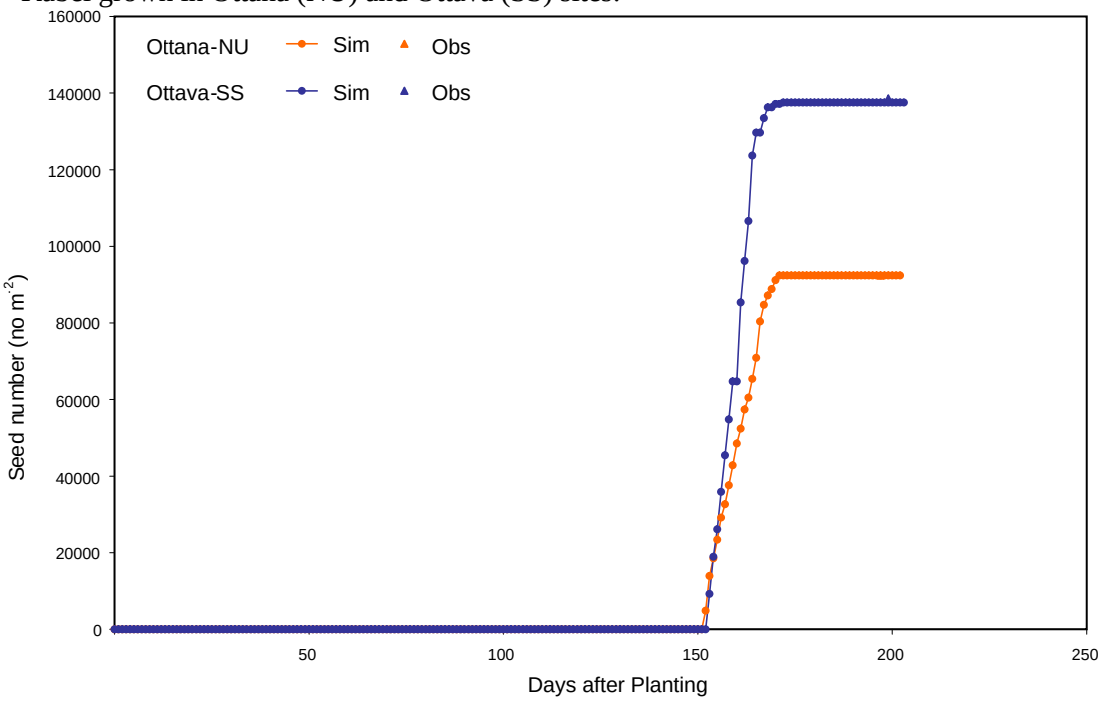
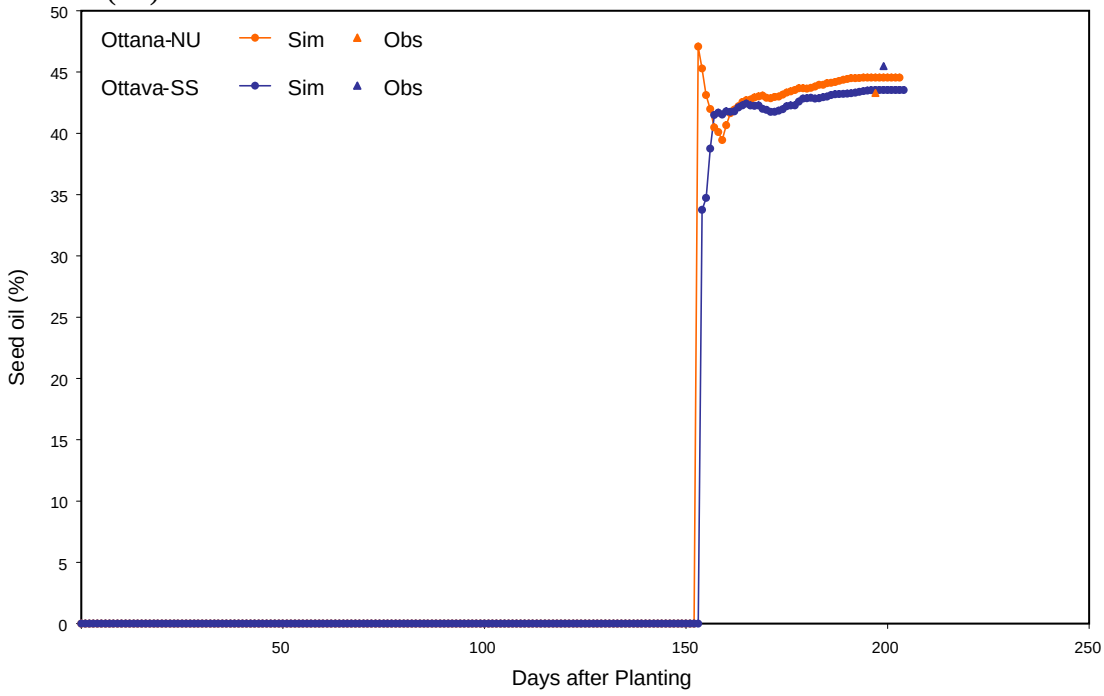
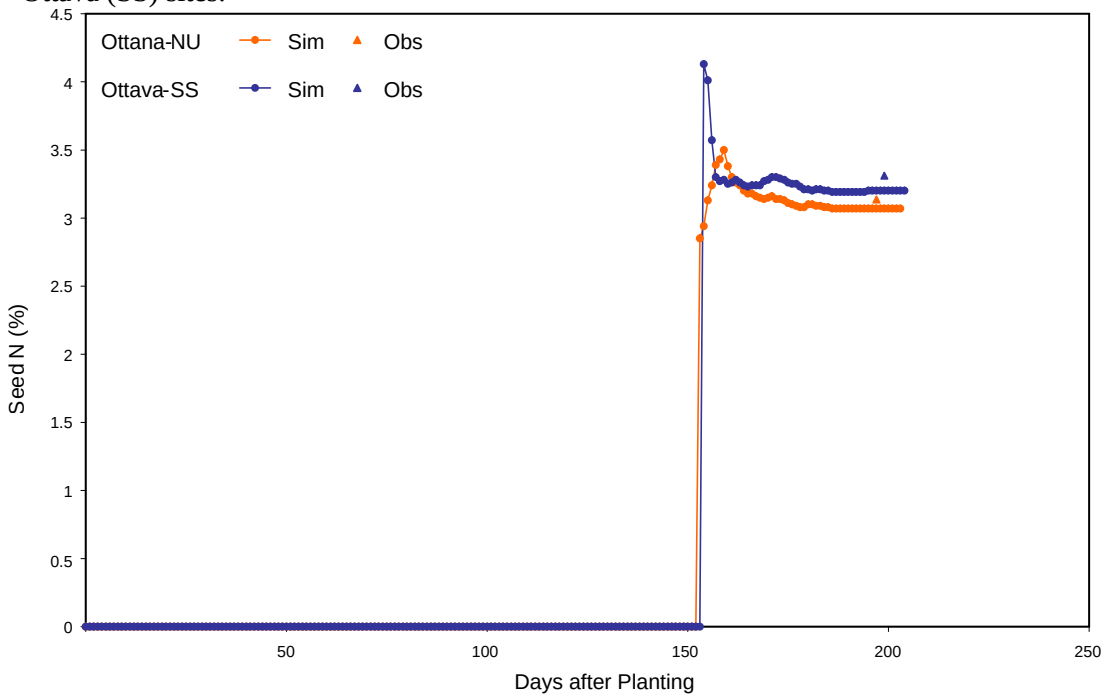



**Figure 4.9.** A comparison of simulated (lines) and observed (symbols) seed oil percent as a function of days after sowing for rapeseed cultivar Kabel grown in Ottana (NU) and Ottava (SS) sites.




Fit of seed oil concentration predictions improved considerably for both sites reducing SDLIP value in ecotype file, but the model slightly overpredict for Ottana site and underpredicted for Ottava site (Table 4.8 and Figure 4.9).

**Figure 4.10.** A comparison of simulated (lines) and observed (symbols) N percent as a function of days after sowing for rapeseed cultivar Kabel grown in Ottana (NU) and Ottava (SS) sites.




Predicted seed N concentrations were slightly underpredicted for both sites (Table 4.8 and Figure 4.10) despite modification toward higher SDPROG parameter in ecotype file.

The pattern of predicted oil and seed N concentration was more realistic after calibration with observed data, however, the calibrated parameter values were generally lower than the literature-based parameters.

### 4.2.6 Senescence

The decline in stem and leaf mass during late season depends on the mobilization rate of proteins and carbohydrates as well as abscission of leaf or petiole (latter from stem pool). Rate of protein mobilization was calibrated to mobilize about two-thirds of the protein from vegetative tissues by the time of maturity. The amount of nonprotein vegetative mass abscised per gram of protein mobilized (SENRTE) was unchanged from soybean value (0.8 g $g^{-1}$). SENRT2, the rate of leaf abscission after physiological maturity, was set to 0.85 higher than default soybean values (0.20), because no leaves were observed in the fields after physiological maturity.

CROPGRO predicts the amount of stem mass abscised as a fraction of the leaf mass abscised (PORPT), based on the assumption that the leaf blade

has a certain mass of attached petiole that is abscised (from the stem mass pool) when the leaf is abscised. For rapeseed, PORPT was set to 0.15 (Table 4.10) lower than soybean (0.58) because rapeseed has smaller petioles than soybean. Decreasing PORPT increased stem mass at maturity.

# 5. SUMMARY AND CONCLUSIONS

The European political debate is mainly focused on energy provision policy, that will likely to be relevant for the coming decades (Commission of the European Communities, 2008). Biofuels are one of the options that are currently pursued to possibly provide a partial contribution to close the energy equation. The EU promotes the use of biofuels as it is thought to contribute to (1) the reduction of fossil fuel energy dependence, (2) reduction of $CO_2$ emissions in the context of the Kyoto protocol and (3) development of rural and agricultural areas through support for the production of biofuel crops (Commission of the European Communities, 2007). However, the use of biofuels is a complex issue. Feedstock for biofuels production is associated with high intensity agriculture, often using monoculture cropping systems with high nutrient input, plant protection products and intensive soil tillage practices.

Rapeseed is the EU's dominant biofuel crop with a share of about 80% of the feedstock. Traditionally, rapeseed is primarily grown for food (vegetable oil), and for feed purposes (cake is used as a high-protein animal feed). Because of the strong incentives and subsidies that were introduced to increase biofuel production, biofuel crops have become a very profitable crop in several countries. In parts of Italy, this has led to the replacement of traditional crops with biofuel crops. The target set by the biofuel directive (European Parliament and the Council, 2003) would demand an enormous increase in biofuel production (and import) and has already led to a 14% increase in the area of rapeseed compared with 2006, and 31.5% relative to the 2002–2006 average (Ollier and Utz, 2007).

In Mediterranean environment, characterized by long, hot and dry summers and short, mild and wet winters, rainfall is usually the most limiting factor for crop growth. Vegetative growth rate is also restricted by low temperatures (0–7 °C) in mid-winter and seed yield is adversely affected by drought (25–40 °C) at the end of the growing season in spring and early summer. Annual crops with early flowering and harvesting are therefore better adapted to these environments (Turner *et al.*, 2001).

Based on current knowledge, rapeseed seems to be one of the most promising energy crop in Mediterranean environment. In particular, winter rapeseed has several advantages over others potential bioenergy crops (e.g. soybean) as (1) an annual crop cycle (rapeseed is currently not irrigated, and incentives or legislation should be

provided that discourage the use of irrigation for the cultivation of biofuel crops in the future), (2) the adaptability to a wide range of pedo-climatic conditions; (3) the ease of introduction into traditional crop rotations; (4) the stability of yield and quality; (5) the competitive profit; (6) the positive energy balance between input and output; (7) the sustainable agro-technique; (8) the tolerance to biotic and abiotic stresses and (9) the availability of suited harvesting and cultivation machines.

A crop modeling approach is needed to evaluate the dynamics of crop growth, the environmental impact and the prediction of the yield and quality output in a varied environment. Crop simulation models are shaped as decision support system (DSS) to be used at different levels: at farm level, in the planning of the agro-business and for the land decision and policy making (e.g. a rapeseed simulation model should allow to consider local differences in water use and nutrient efficiency that may lead to better-informed land use and policy decisions). Many software-based simulation models are available for different crops. However, none of these models refer to productive systems based on rapeseed crop.

The objective of this research was to develop a tool to predict the growth and yield of rapeseed that responds to environmental and management inputs. In this effort, a rapeseed growth study was conducted in the 2007-08 and 2008-09 growing seasons. We used information from these experiments to supplement the existing literature in an effort to adapt the CSM version of the CROPGRO model to simulate the growth and yield of rapeseed.

*Development of species file parameters for rapeseed*

New species, cultivar, and ecotype files were created to allow simulation of rapeseed growth and yield with CROPGRO. Two field experiments were carried out and the measured data collected were used to test the model. The fit of the crop cycle and biomass predictions from the trials-based species file were good with an index of agreement (d-index) of 0.98 and a RMSE of 932.5 kg $ha^{-1}$. Fit of LAI was not as accurate with a d-index of 0.65 and an RMSE of 0.58 and a tendency to overpredict LAI soon after the occurrence of LAI peak.

On review of the results, there appeared to be some features of CROPGRO that may have made significant contributions to the errors in predicting yield components.

In order to better mimic the rapeseed biology, modifications must be made to the model code itself. Conclusive values for critical daylenght and daylenght sensitivity for Kabel cultivars could not yet be determined. According to Daniels, Scarisbrick and Smith (1986), phenological development of winter oilseed rape is an important aspect of the yield formation process because the time of flowering depends on the combined effect of photoperiod and temperature. Moreover, CROPGRO model does not simulate vernalization, thus to improve robustness of the model the effect of photoperiod and vernalization on the growth and yield of winter oilseed rape needs to be assessed by planning trials with different planting date and conducting researches in areas with different daylight hours than Sardinia.

According to Sinclair and De Wit (1975), the main reason for the facilitation of leaf senescence in crops after the formation of pods is that pods become a sink for nitrogen and induce translocation of N from leaves and stems. This does not stop photosynthesis in the vegetative parts, but reduces its efficiency and accelerates senescence because of a N deficiency. Gabrielle *et al*. (1998) added the following explanation about the facilitation of leaf senescence in rapeseed after the commencement of pod formation. The formation of pods shades the underlying leaves and as a result the radiation available to these leaves is reduced and leaf senescence hastened.

Consideration of these differences notwithstanding, the overall performance of trials-based parameters was good. The bulk of future efforts should be directed at changing the model code to more accurately reflect the life cycle of rapeseed.

*Implications of the research*

As the first working version, the modified soybean version of CROPGRO CSM model marks a starting point in adapting the model to represent the biology and management of rapeseed. Parameters may be easily adjusted as new knowledge (photoperiod, senescence etc.) becomes available. Adaptation to other Brassicas (e.g. *Brassica carinata*) should be much simpler with the new version's structure. Given these advances, additional testing and calibration is still needed to improve the robustness of the model for general use. Beyond the added utility of the model, the performance may be adequate to use under limited conditions. Accurate prediction of single season production may be a ways off, limiting its usefulness to farmers and consultants looking for a tool to make midseason management changes. However,

multi-year simulations comparing relative differences between management strategies may produce useful results regarding grain production and even grain oil and N content.

*Future research*

The most immediate priority to further model development is to identify the cause of the excessive LAI prediction after flowering. Once that is done, other parameters can be recalibrated. The next step beyond that would be to test the temperature parameters over a wider range of conditions. Addressing those two concerns should improve the usefulness of the model considerably. Confidence in shorter-term simulation results should increase. After this, use of the model in long and short-term testing of nutrient management strategies and use of the results in directing research priorities may be quite viable. Looking in new directions for improving the model, we should look to the potential users. As farmers are the ultimate users of rapeseed, the priorities of the model should extend in that direction. The rapeseed version of CROPGRO already could predict specification for rapeseed oil (e.g. density, ash content, phosphorus content, caloric values). From these variables, a new output file could be created to provide information targeted to vegetable oil performance.

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