Use of crop growth models in DSS for Agricultural Water Management

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System, Models and Simulation - definitions

- A system is a limited part of reality that contains inter-related elements – exists and operates in time and space
- Agricultural system – soil, crops (vegetation), atmosphere, management practices..
- A model is simplified representation of a system – *a system* of postulates, data and inferences presented as a mathematical description of an entity or state of affairs
- Simulation is the process of running (manipulation) of models under specific conditions (scenarios) and the study of their behavior in reference to that of the system they present

Why generating models?

- They help to explain the processes from the nature (relate variables involved in processes following fundamental laws)
- As research tool they help to interpret experimental results on the basis of scientific hypothesis
- They help to integrate multi-disciplinary works (IL&WRM)
- They are scenario simulators (what … if …. analysis)
- They help in real-time decision making processes, management, (when to irrigate, which crop, what is the amount of water to supply)
- They are predictive tools for resources optimization on the long time (e.g. season …)

Mathematical models – descriptive and explanatory

- Mathematical models:
  - descriptive (statistical, stochastic) and
  - explanatory (deterministic, physically-based processes)
- A descriptive model describes behavior of a system in a relatively simple manner and reflects little or none of the mechanisms that are the causes of that behavior – it is *derived from statistical relationship* between the variables studied.
- An explanatory model consists of quantitative description of the main processes, interlinked and *integrated on the basis of physical understanding of the processes* at different levels (e.g. CO_2-light response curve of a single leaf is integrated with other processes to explain crop growth)

General model's characteristics

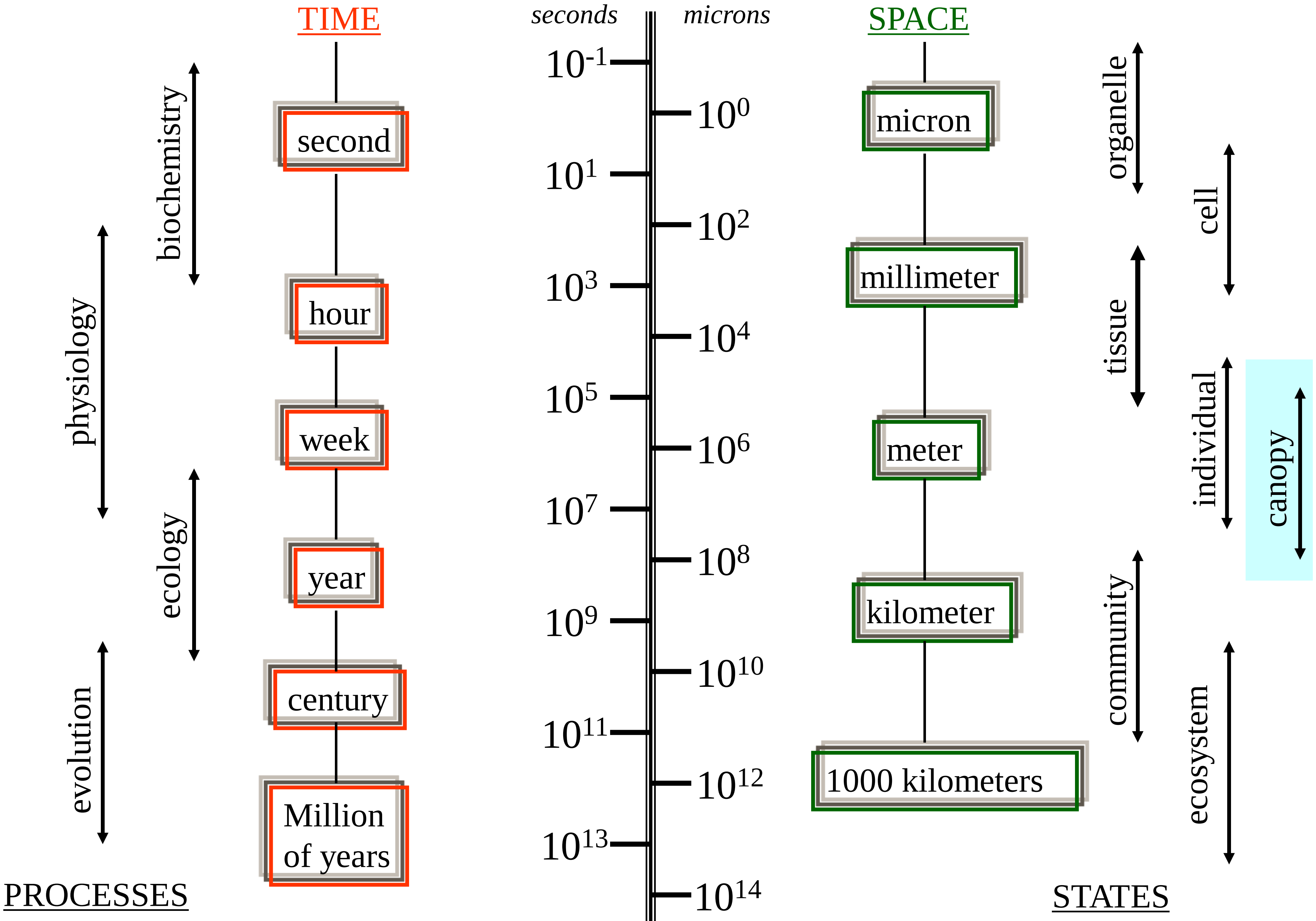
- Empirical – attempt mainly description of behavior and trends
- Mechanistic – attempt description with understanding of processes

- Static – do not contain time as variable
- Dynamic – explicitly contain time as variable

- Deterministic – make definitive prediction for quantities without any associated probability distribution
- Stochastic – contain some random elements or probability distribution, so that they do not only predict the expected value of a quantity, but also its variance

Crop growth models characteristics

- Generally, they are:
  - **Mechanistic**
  - **Dynamic**
  - **Deterministic**
- Furthermore, they imply the considerations related to:
  - **Space-time scale**
  - **Hierarchy of processes**



TIME

second

hour

week

year

century

Million of years

seconds

10^{-1}

10^{1}

10^{3}

10^{5}

10^{7}

10^{9}

10^{11}

10^{13}

microns

10^{0}

10^{2}

10^{4}

10^{6}

10^{8}

10^{10}

10^{12}

10^{14}

SPACE

micron

millimeter

meter

kilometer

1000 kilometers

biochemistry

physiology

ecology

evolution

PROCESSES

organelle

cell

tissue

individual

canopy

community

ecosystem

STATES

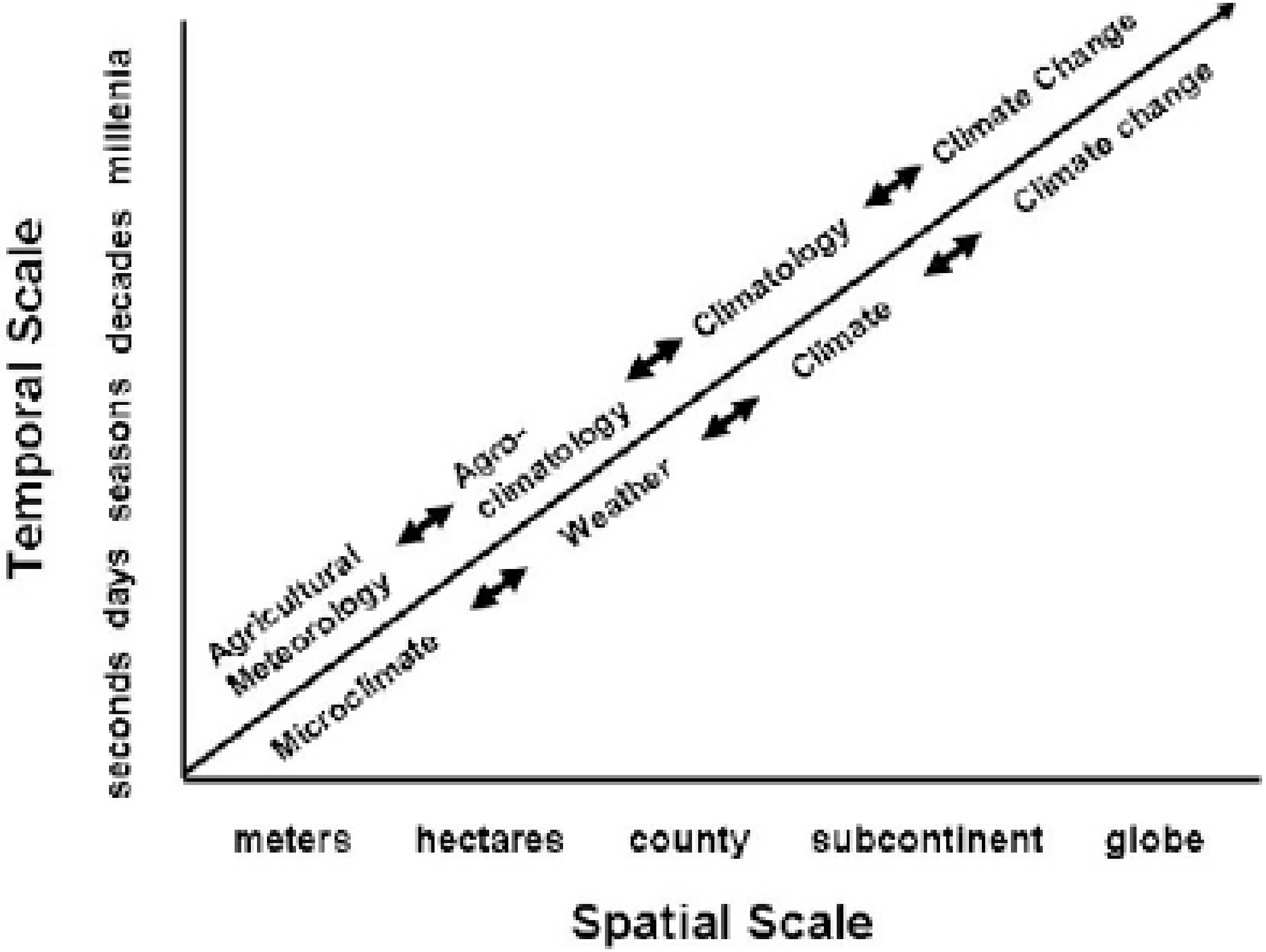
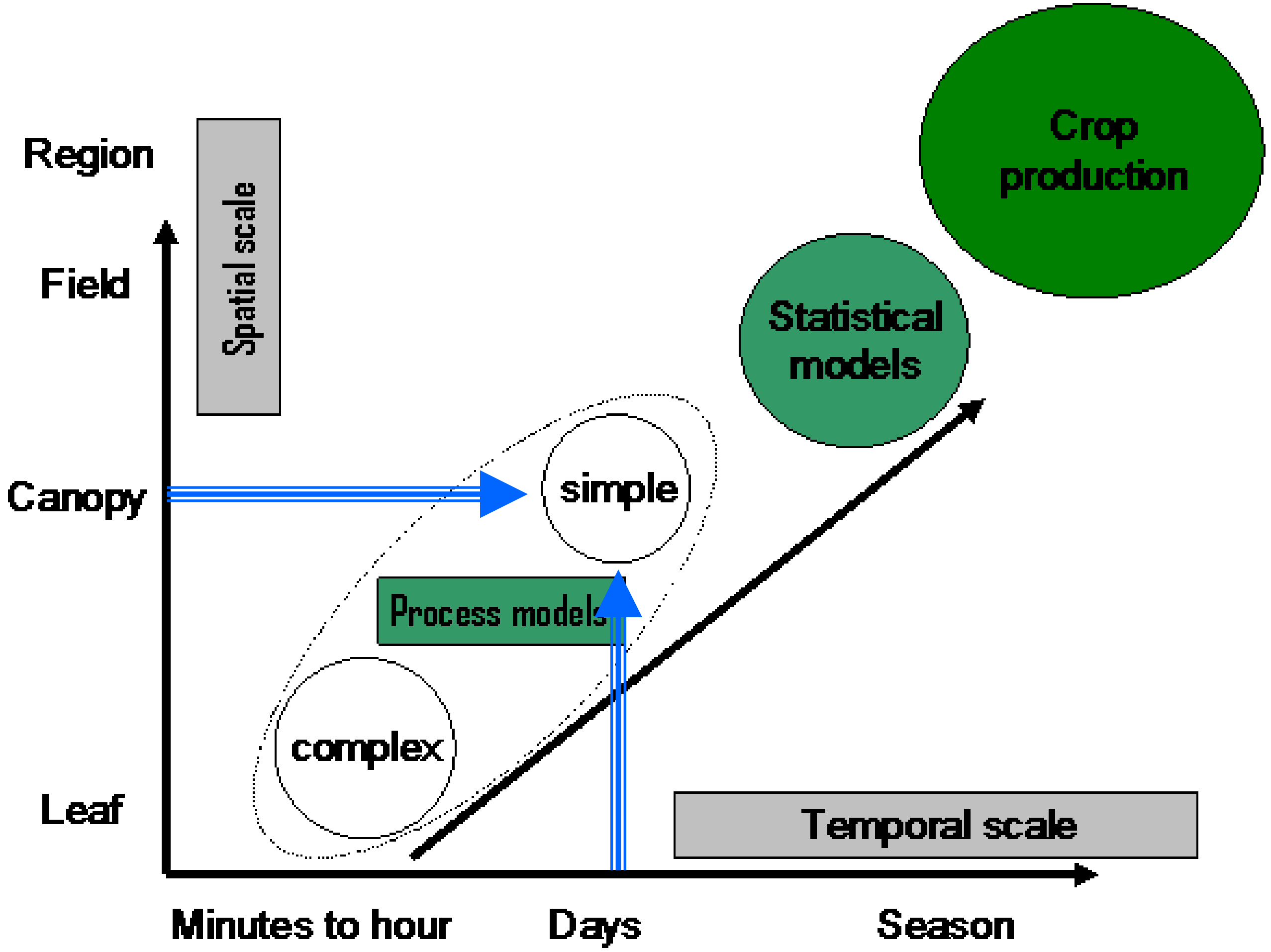


Fig. 1. Generalized temporal and spatial scaling of agricultural meteorology, agroclimatology, climatology, and climate change.

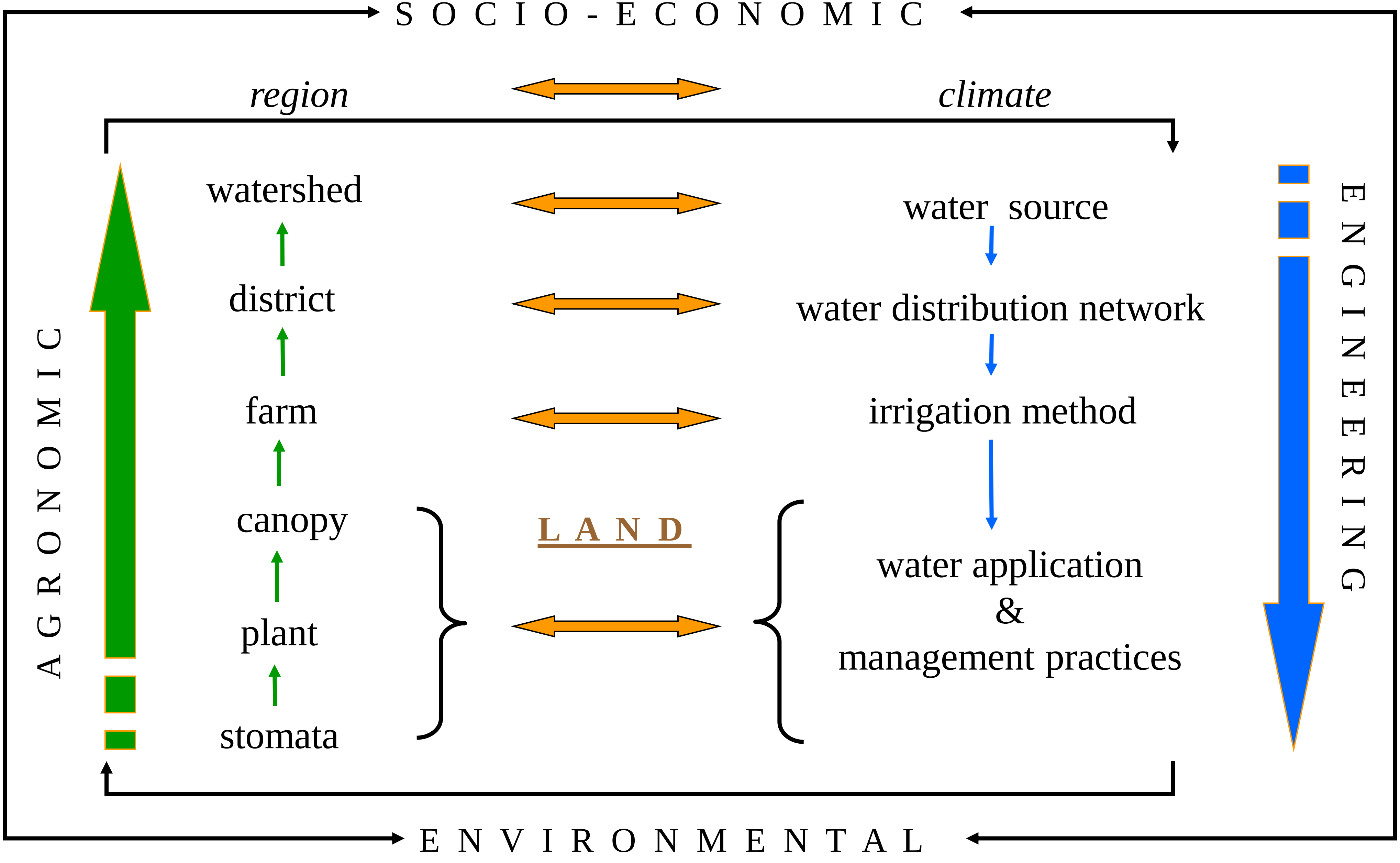
Source; Steiner and Hatfield, 2008

Schematic illustrations of crop modeling approaches: types of models in relation to levels of spatial (leaf, canopy, field) and temporal (minutes to hour, days, seasons) scales



(redrawn from Tubiello and Ewert, 2003)

Interaction between the scales and issues



SOCIO-ECONOMIC

region *climate*

watershed water source

district water distribution network

farm irrigation method

canopy

plant

stomata

LAND

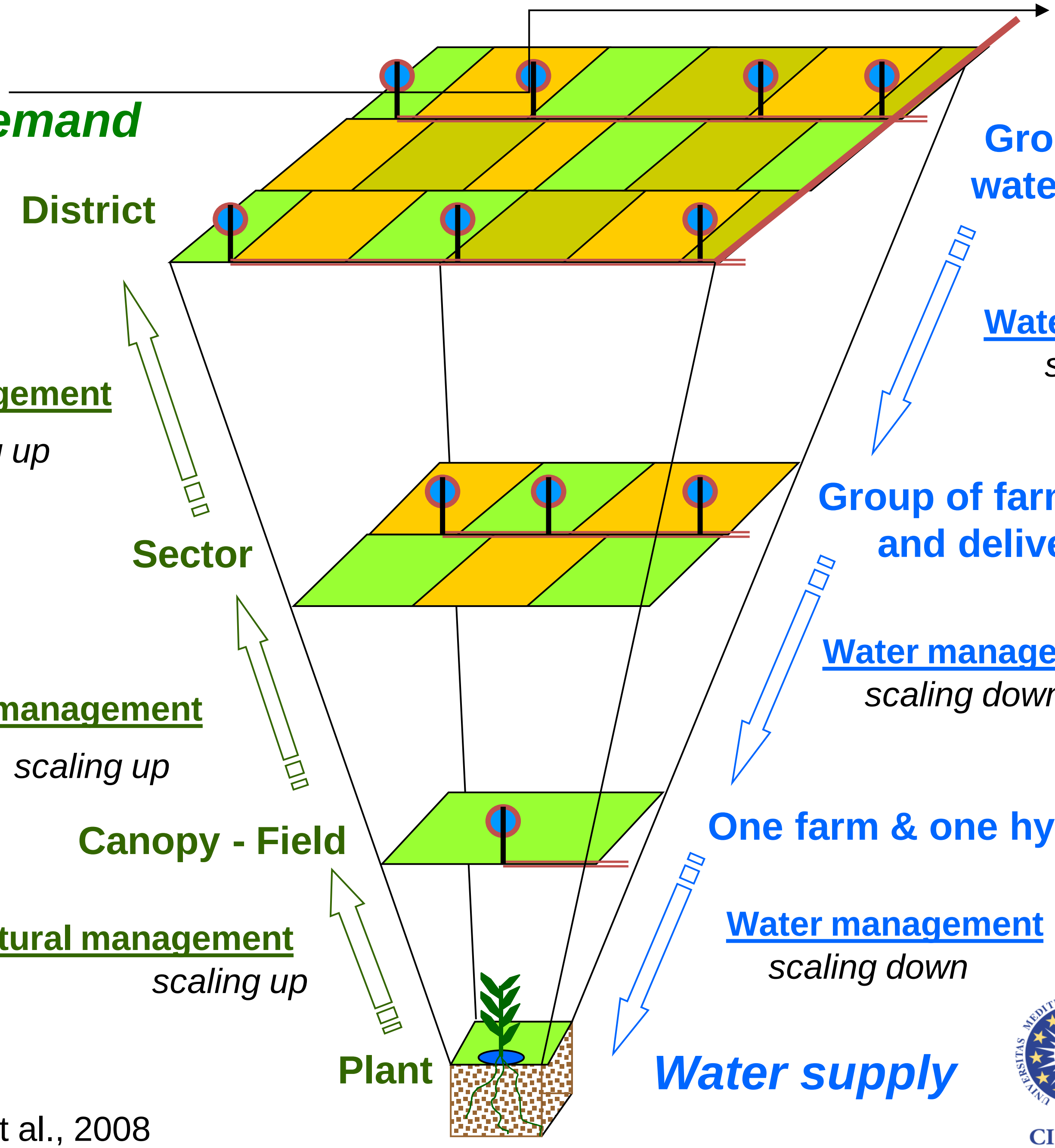
water application
&
management practices

AGRONOMIC

ENGINEERING

ENVIRONMENTAL

AGRONOMIC AND ENGINEERING ASPECTS OF WATER MANAGEMENT IN AGRICULTURE



Source of water

Water demand

District

Group of sectors and water delivery network

Agricultural management

scaling up

Water management

scaling down

Sector

Group of farms, group of hydrants and delivery network branch

Agricultural management

scaling up

Water management

scaling down

Canopy - Field

One farm & one hydrant

Agricultural management

scaling up

Water management

scaling down

Plant

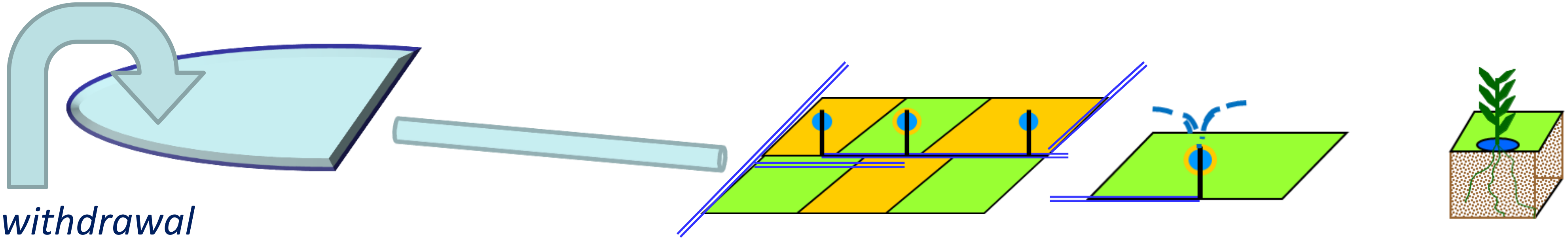
Water supply

LAND and WATER
Resource Management

CIHEAM

Source: Todorovic et al., 2008

Water Efficiency in agriculture: engineering/agronomic aspects



withdrawal

accumulation	*conveyance*	*Farm distribution*	*Irrigated plot*	*Plant root zone*
Water storage *(evaporation, leakage)*	Water conveyance *(leakage, evaporation)*	Water distribution *(leakage, evaporation)*	Water application *(evaporation, runoff, deep percolation)*	Water effectively used by crop, transpired
EFF_{stor}	EFF_{conv}	EFF_{distr}	EFF_{app}	
		Irrigation network	*Irrigation management*	

Efficiency

Engineering aspects →

← Agronomic aspects

Cropping pattern & growing period	*Land/soil/crop management*

$WUE_{agriculture}$ = f(Engineering & Agronomic performance)

For each crop *i* (i=1,…,N, where N is total number of crops) cultivated on surface area *A* with seasonal crop evapotranspiration ET_c, effective precipitation P_{eff} and irrigation application efficiency EFF_{app}

Agricultural Water Demand (WD)

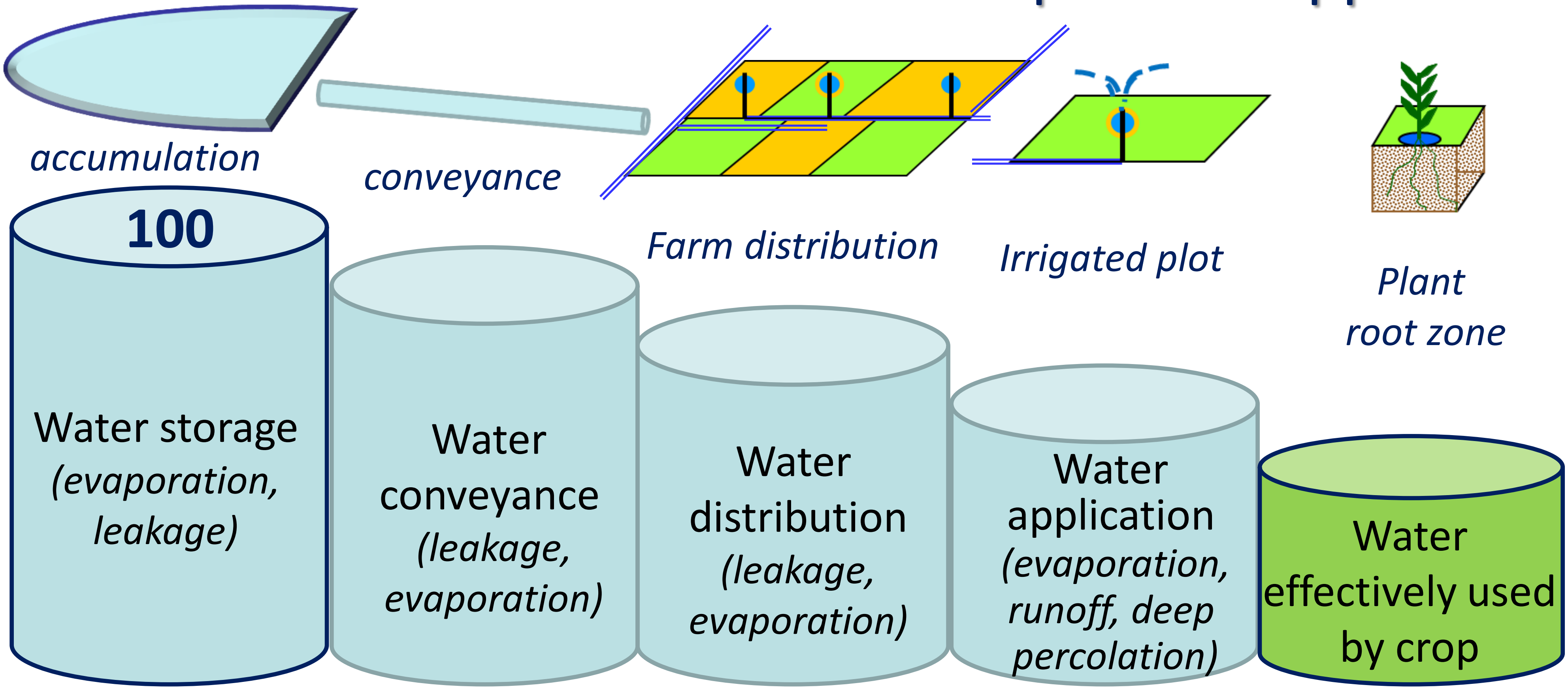
$$WD = \sum_{i=1}^{N} \left(\frac{ET_c - P_{eff}}{EFF_{app}} A\right)_i$$

Engineering Water Supply (WS) = Agricultural Water Demand (WD)

Engineering Water Withdrawal for irrigation (**WW**) depends on engineering efficiency of *j* management steps (j=1,…, M, where M is total number of steps, e.g. withdrawal, storage, conveyance, distribution, …)

$$WW = \frac{WD}{\prod_{j=1}^{M} EFF_j} = \frac{\sum_{i=1}^{N}\left(\frac{ET_c - P_{eff}}{EFF_{app}} A\right)_i}{\prod_{j=1}^{M} EFF_j} = \frac{\boldsymbol{Agricultural\ demand}}{\boldsymbol{Engineering\ efficiency}}$$

Water Efficiency Chain from accumulation to the plant: multiplicative approach



accumulation

conveyance

Farm distribution

Irrigated plot

Plant root zone

100

Water storage *(evaporation, leakage)*

Water conveyance *(leakage, evaporation)*

Water distribution *(leakage, evaporation)*

Water application *(evaporation, runoff, deep percolation)*

Water effectively used by crop

Efficiency	EFF_{stor}		EFF_{conv}		$\text{EFF}_{\text{distr}}$		EFF_{app}	
low	*0.9*	*	*0.85*	*	*0.8*	*	*0.75*	**45.9**
medium	*0.9*	*	*0.85*	*	*0.85*	*	*0.85*	**55.3**
high	*0.95*	*	*0.9*	*	*0.9*	*	*0.9*	**65.6**

Exercise:

- One crop, cultivated under irrigation over a surface area of A=1000 ha, had seasonal ET=500 mm and effective precipitation of 100 mm. What was the gross agricultural water demand if application efficiency $EFF_{app}=0.8$?
- What was the engineering water withdrawal if storage efficiency $EFF_{stor}=0.9$, conveyance efficiency $EFF_{conv}=0.9$ and distribution efficiency $EFF_{distr}=0.8$?
- What were the overall water losses?
- What could be overall the seasonal water saving if application efficiency EFF_{app} would be increased from 0.8 to 0.9?
- What could be the extension of cultivated/irrigated land if all water saved by increase of application efficiency (from 0.8 to 0.9) is used for irrigation of the same crop?

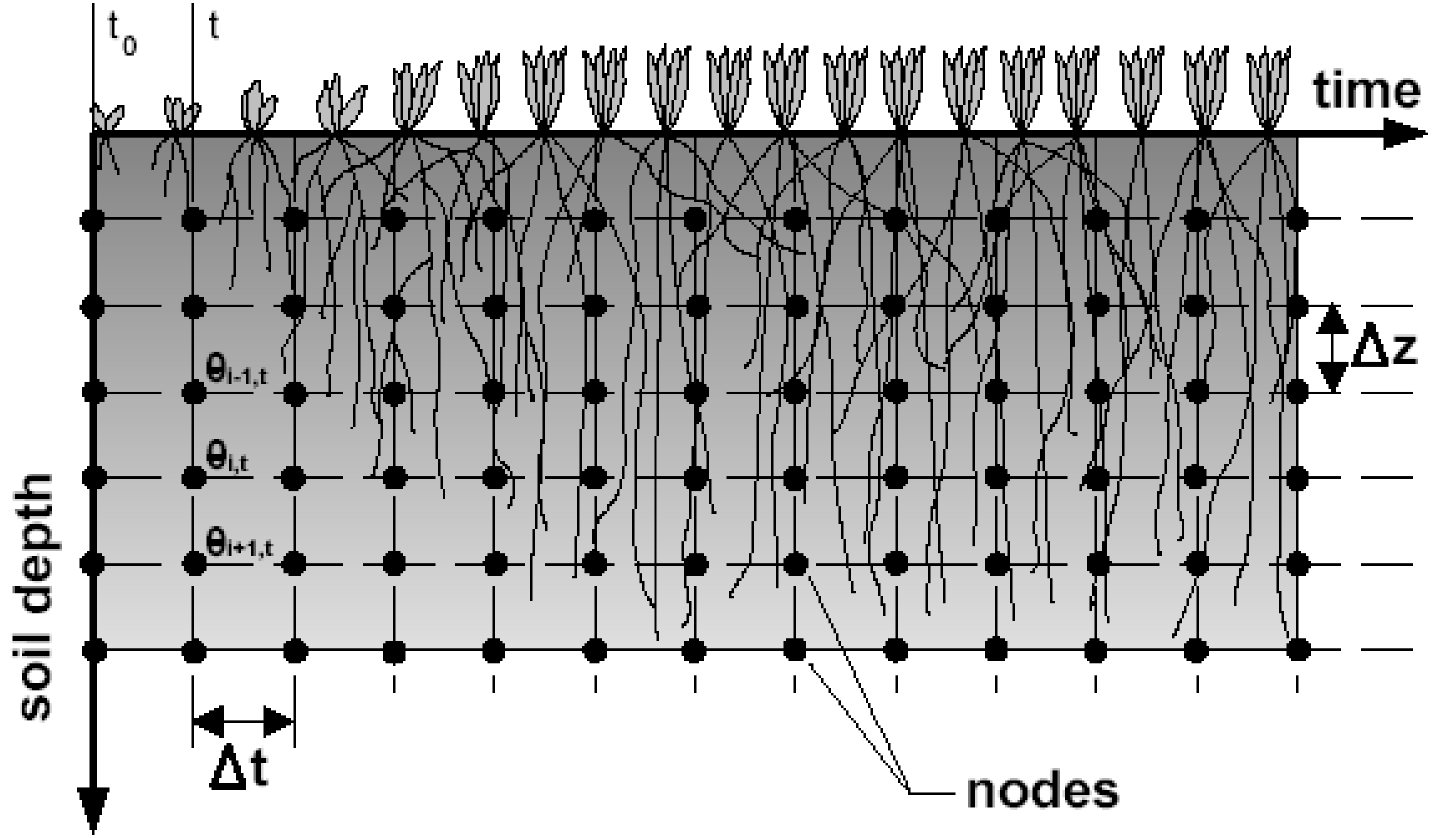
Dynamic crop growth models – state-rate variable approach

- Assumption: the state of the system can be quantified at any moment and the changes in the system can be described by mathematical equations.
- State variable approach models distinguishes between state, driving and rate variables
- State variables – quantities such as amount of water in the soil, LAI, biomass…
- Driving variables (forcing functions)- characterize the influence of external factors on the system but are not influenced by the processes within the system (e.g. macro-meteorological variables: air temperature, radiation, precipitation).
- Rate variables – indicate the rate at which the state variables change at a certain moment, and over a certain time step Δt – rate variables are calculated on the basis of the state and driving variables (transpiration rate, CO_2 assimilation rate...)
- After calculating the values of all rate variables, they are used to calculate the new value of the state variables by numerical integration as:

$$STATE(t+\Delta t)=STATE(t)+RATE(t)*\Delta t$$

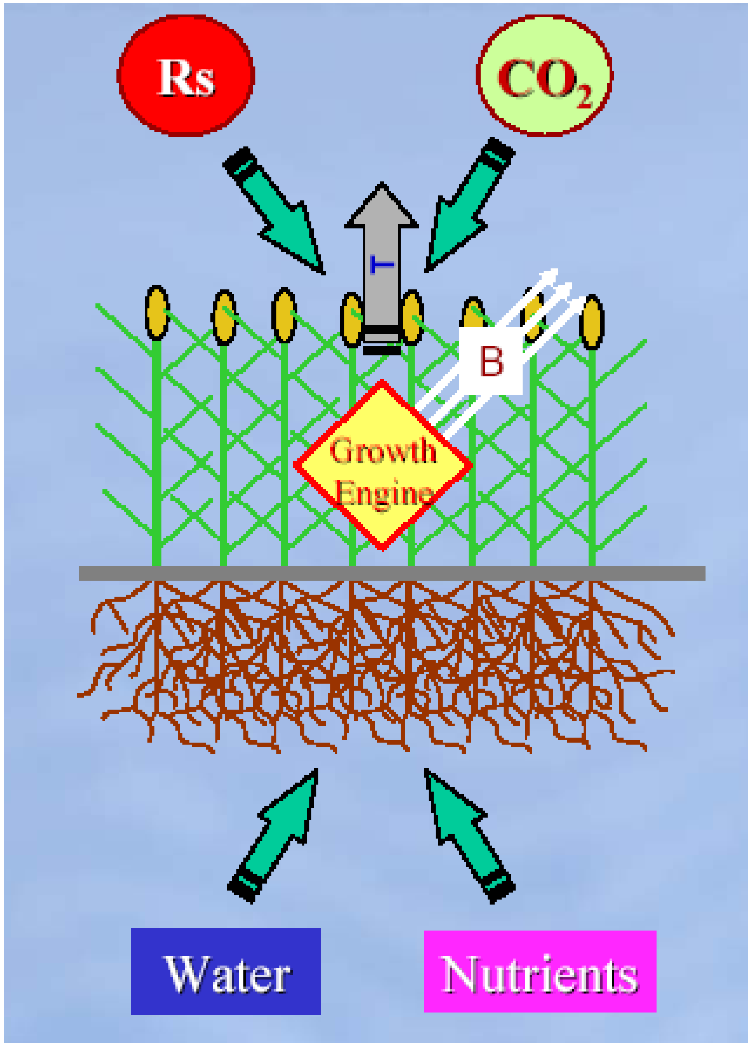
A time (t) – depth (z) grid
for the solution of the SWB with a dynamic soil water simulation model

STATE(t+Δt)=STATE(t)+RATE(t)*Δt

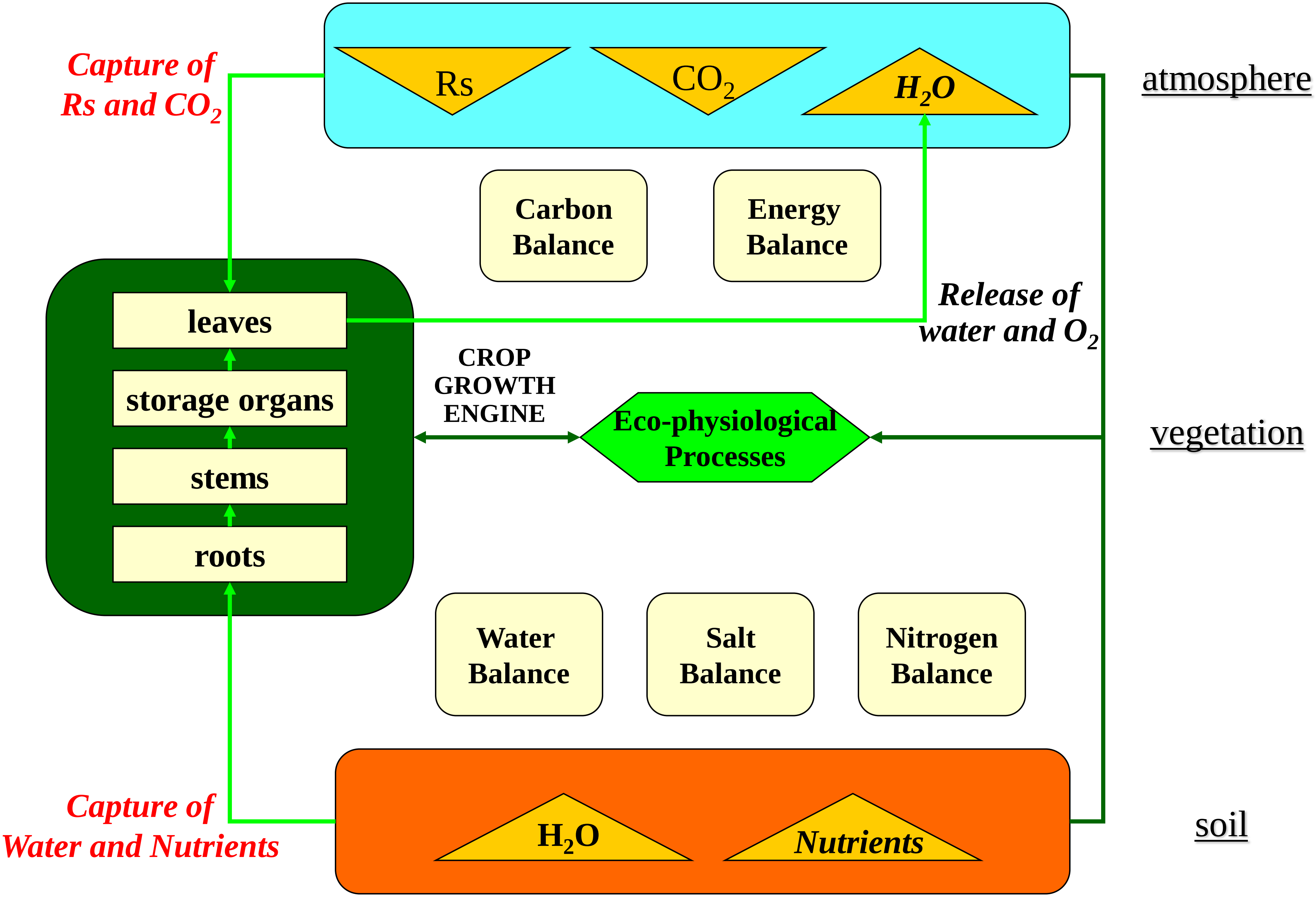


Source: Raes, 2004

Crop growth engines – capture and use of environmental resources



Source: Steduto, 2005



Capture of
Rs and CO_2

Rs

CO_2

H_2O

atmosphere

Carbon Balance

Energy Balance

leaves

storage organs

stems

roots

Release of
water and O_2

CROP
GROWTH
ENGINE

Eco-physiological Processes

vegetation

Water Balance

Salt Balance

Nitrogen Balance

Capture of
Water and Nutrients

H_2O

Nutrients

soil

Driving forces (growing engines) and processes of a crop growth model

Source: Todorovic, 2005

Crop Growth Models driving equations

CropSyst

$$AGB_T = \frac{K_{BT} \cdot T}{VPD}$$

$$AGB_{IPAR} = RUE \cdot IPAR \cdot T_{\lim}$$

$$AGB = \min(AGB_{IPAR}, AGB_T)$$

WOFOST

$$A_p = A_m \cdot (1 - e^{\frac{-\varepsilon PAR_a}{A_m}})$$

$$A = \frac{T_a}{T_p} \cdot A_p$$

$$\Delta W = C_e \cdot (A - R_m)$$

AquaCrop

$$AGB = w_p \frac{T_c}{ET_o}$$

Crop growth models – production levels

- Potential production: absolute production for a given crop when grown in a given area under specific weather conditions with an optimum water and nutrient supply, thorough pest and weed control and without diseases.
- Attainable (limited) production:
  - Water-limited production – when soil moisture was below/above an optimum level causing water/oxygen shortage for the plant roots
  - Nutrient-limited production – when the soil nutrient availability (N, P, K) is below the crop nutrient requirements
- Reduced production: the production level for farming without pest and/or weed control and diseases (rarely considered in crop growth models).

Crop growth models – construction phases

1. Definition of the boundary conditions of the system to model and objectives
2. Data availability and relevance for the model
3. Analysis of hierarchies and space-time scales of processes involved
4. Algorithm formulation and parameterization
5. Software implementation
6. Running test
7. Calibration
8. Validation
9. Sensitivity analysis

Crop growth models – conditions and scales

- Boundary conditions:
  - Location – latitude, altitude
  - Soil characteristics – depth, soil water holding capacity
  - Crop calendar – sowing/planting day, length of growing season, height, root depth …
- Initial conditions:
  - Soil water status
  - Soil nitrogen status
- Simulation scales:
  - Daily – for soil water balance, energy balance and crop growth
  - Seasonal – for soil nitrogen balance

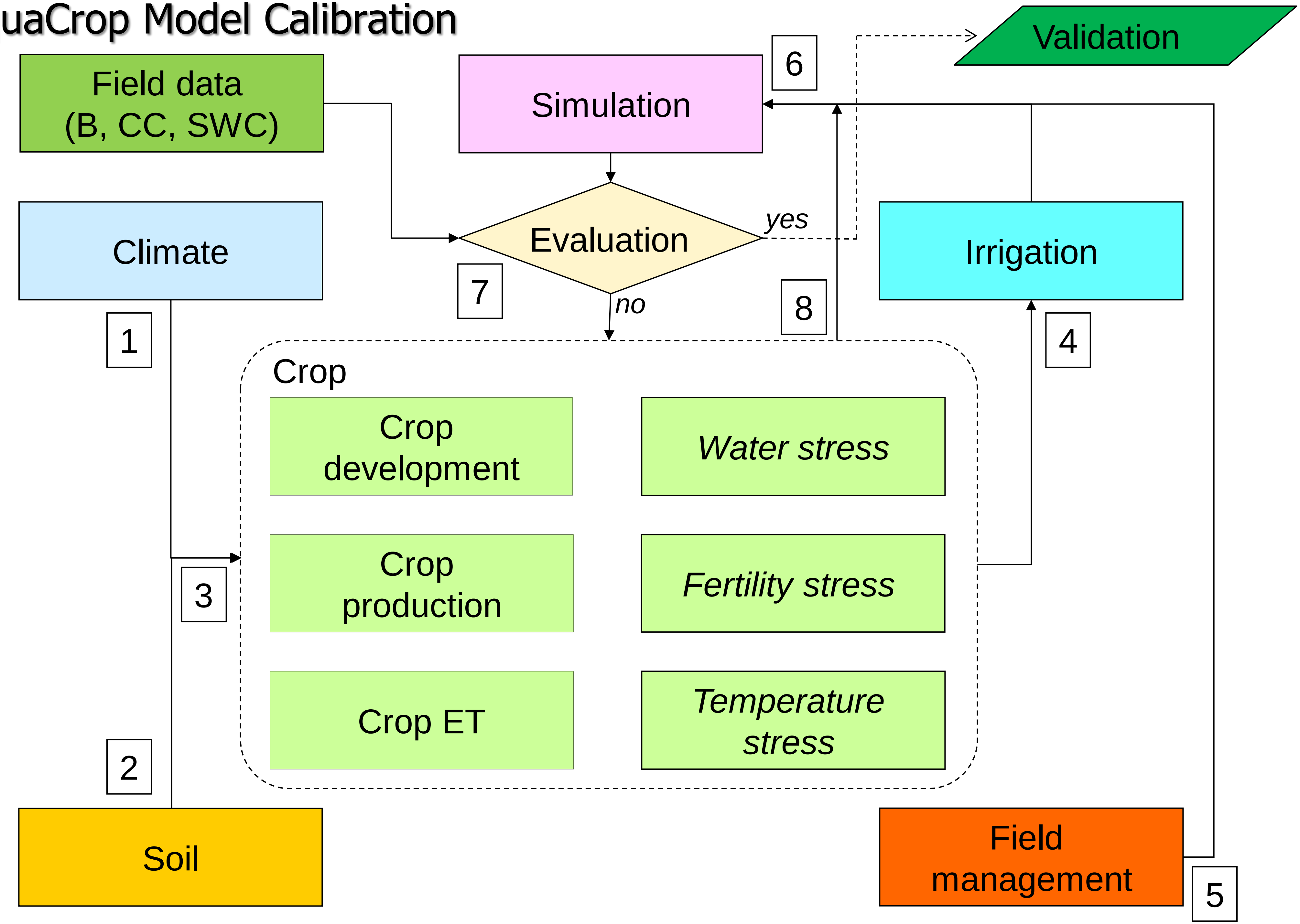
Crop growth models – requirements

- Available data (not difficult to obtain?):
  - Location – latitude, altitude
  - Climate – daily temperature, precipitation, radiation, humidity, wind, pan evaporation
  - Soil – texture, depth, water availability, nutrient availability
  - Crop – type, cultivars, planting date, growing stages.
  - Management – irrigation, fertilizer application, tillage…
- Model should maintained a balance of all parts such as soil-plant-atmosphere interaction, water balance, energy balance, carbon balance, nitrogen balance…
- Main assumptions and simplifications should be clearly indicated.
- Model must have been calibrated using real data sets.
- Model must have been tested (validated) under field conditions on data sets other than those on which it was calibrated.

Model's calibration

- CGM must be calibrated and validated for the specific soil-water-crop-management conditions - there is no an universal model that will work with an unaltered set of parameters for all conditions.
- Calibration is needed to account for the empiricism which is often at the base of the relations used in a model.
- **Calibration** is the process of adjustment of model parameters to fit model outputs to measured (experimental) data.
- The adjustment of model's parameters must be done within a range pre-defined for the parameters.
- Models should be calibrated initially for the optimal growing conditions (water, nutrient, temperature) and only there after should be calibrated the parameters that quantify the effects of stress on crop growth.

AquaCrop Model Calibration



Field data
(B, CC, SWC)

6

Simulation

Validation

Climate

Evaluation

yes

no

7

8

Irrigation

1

4

Crop

Crop development

Water stress

Crop production

Fertility stress

3

Crop ET

Temperature stress

2

Soil

Field management

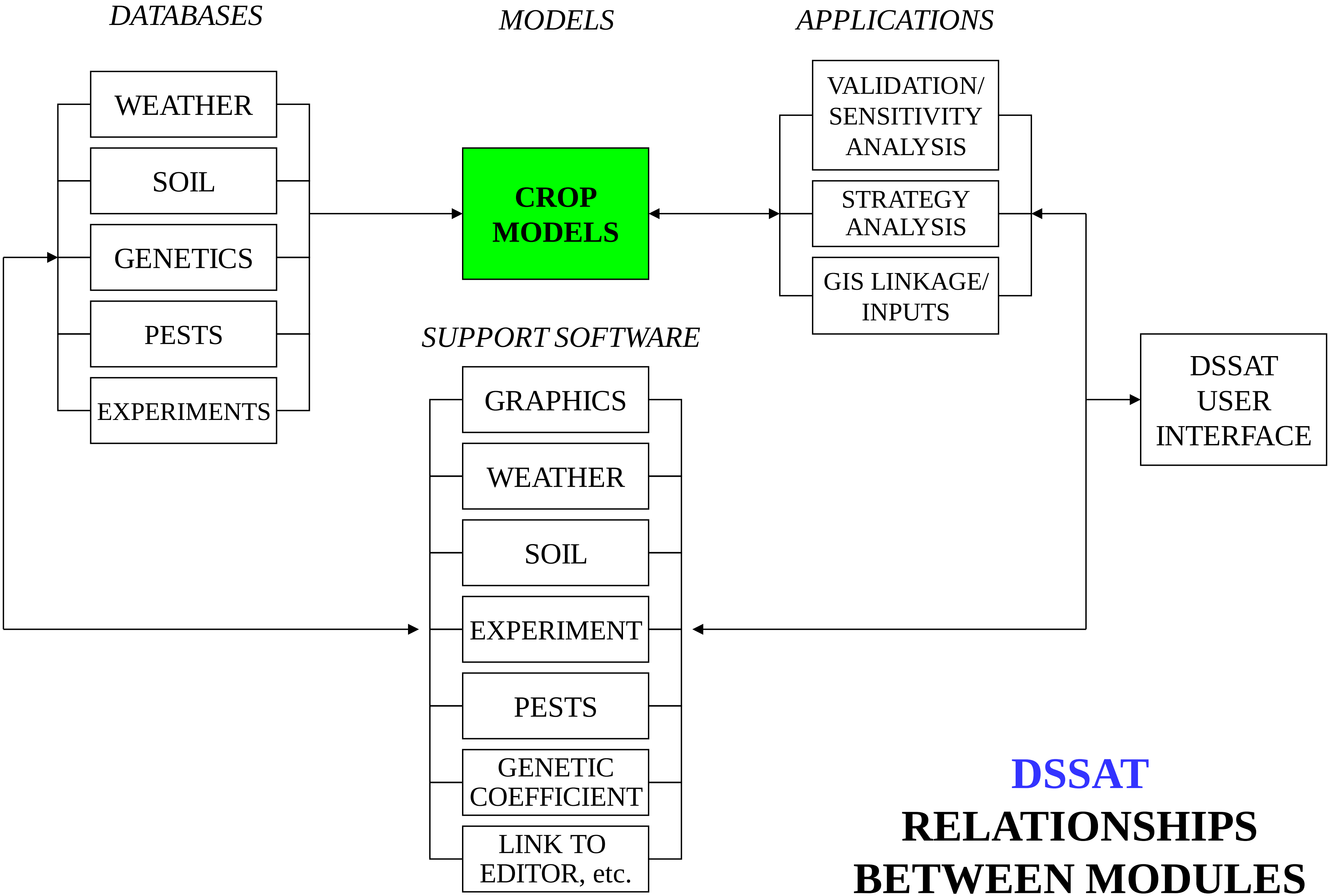
5

Model’s validation

- CGM should be validated under different environmental and management conditions to evaluate their accuracy on overall biomass/yield prediction as well as the performance of major processes/modules of the model.
- Model’s validation can be affected by:
  - the errors in the programming code (occur usually in the early stage of model development);
  - the errors in the calibration procedure;
  - the errors in the input parameters and experimental data;
  - Inadequacy of the model for the specific purposes

Crop Growth Modeling – North American School

- CERES (Crop-Environment Resource Synthesis) model
  - Crop (species) specific: CERES-Wheat, CERES-Maize, CERES-Barley, CERES-Sorghum, CERES-Rice, CERES-Millet
- CROPGRO models
  - legumes (faba bean, broad bean, dry-bean, soybean), tomato, chickpea, sugarcane, sunflower, peanut, potato (CROPSIM-SUBSTOR)
- CROPSYST
  - Multi-crop, multi-year, developed as a management oriented tool
- DSSAT (Decision Support System for Agrotechnology Transfer)
  - a modular, interactive, management oriented tool for system analysis
  - Composed of crop growth simulation modules of CERES and CROPGRO families of models and common components for soil water, soil nitrogen, weather and sensitivity analysis.



DATABASES

- WEATHER
- SOIL
- GENETICS
- PESTS
- EXPERIMENTS

MODELS

CROP MODELS

APPLICATIONS

- VALIDATION/ SENSITIVITY ANALYSIS
- STRATEGY ANALYSIS
- GIS LINKAGE/ INPUTS

SUPPORT SOFTWARE

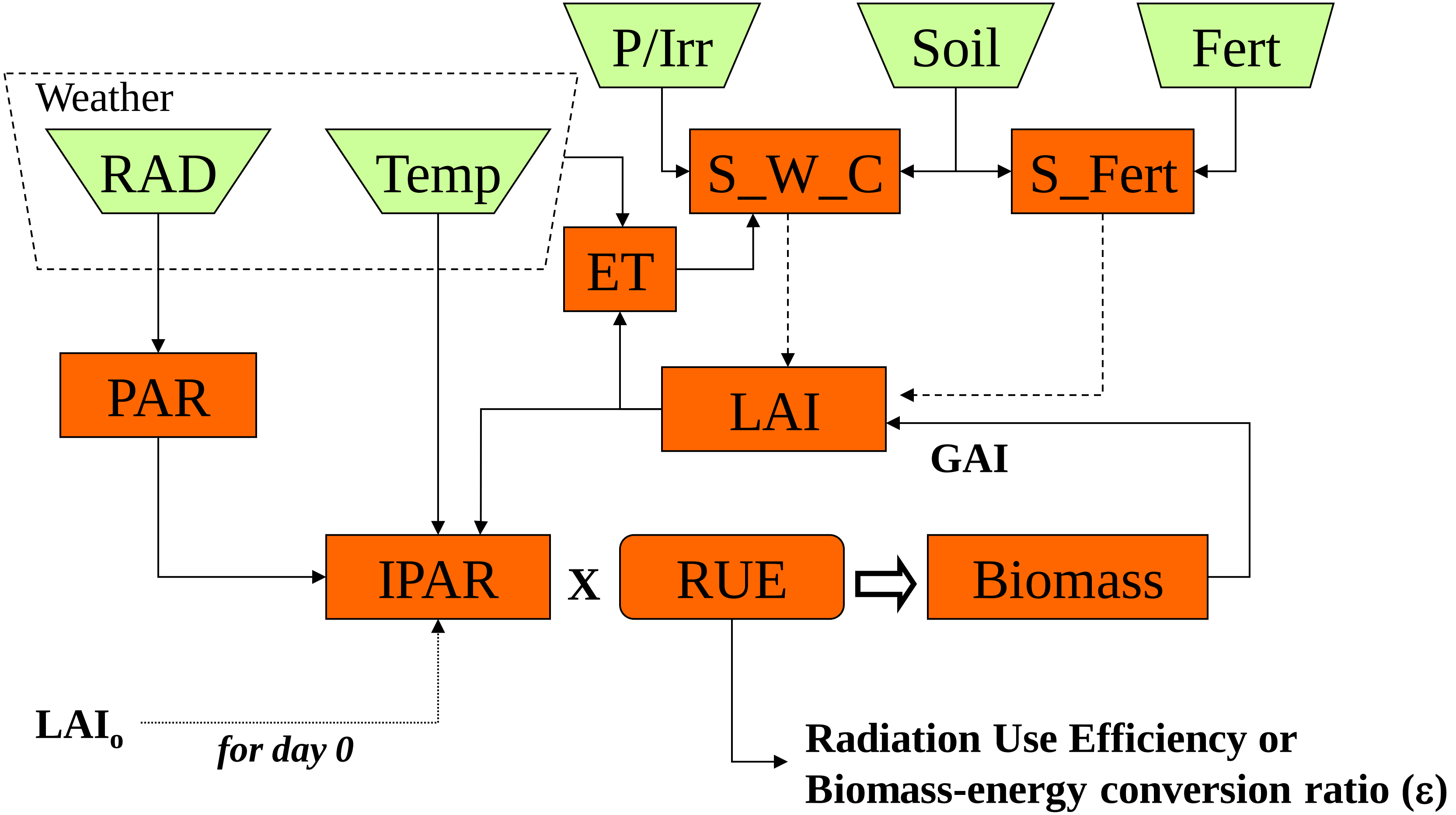
- GRAPHICS
- WEATHER
- SOIL
- EXPERIMENT
- PESTS
- GENETIC COEFFICIENT
- LINK TO EDITOR, etc.

DSSAT USER INTERFACE

DSSAT RELATIONSHIPS BETWEEN MODULES

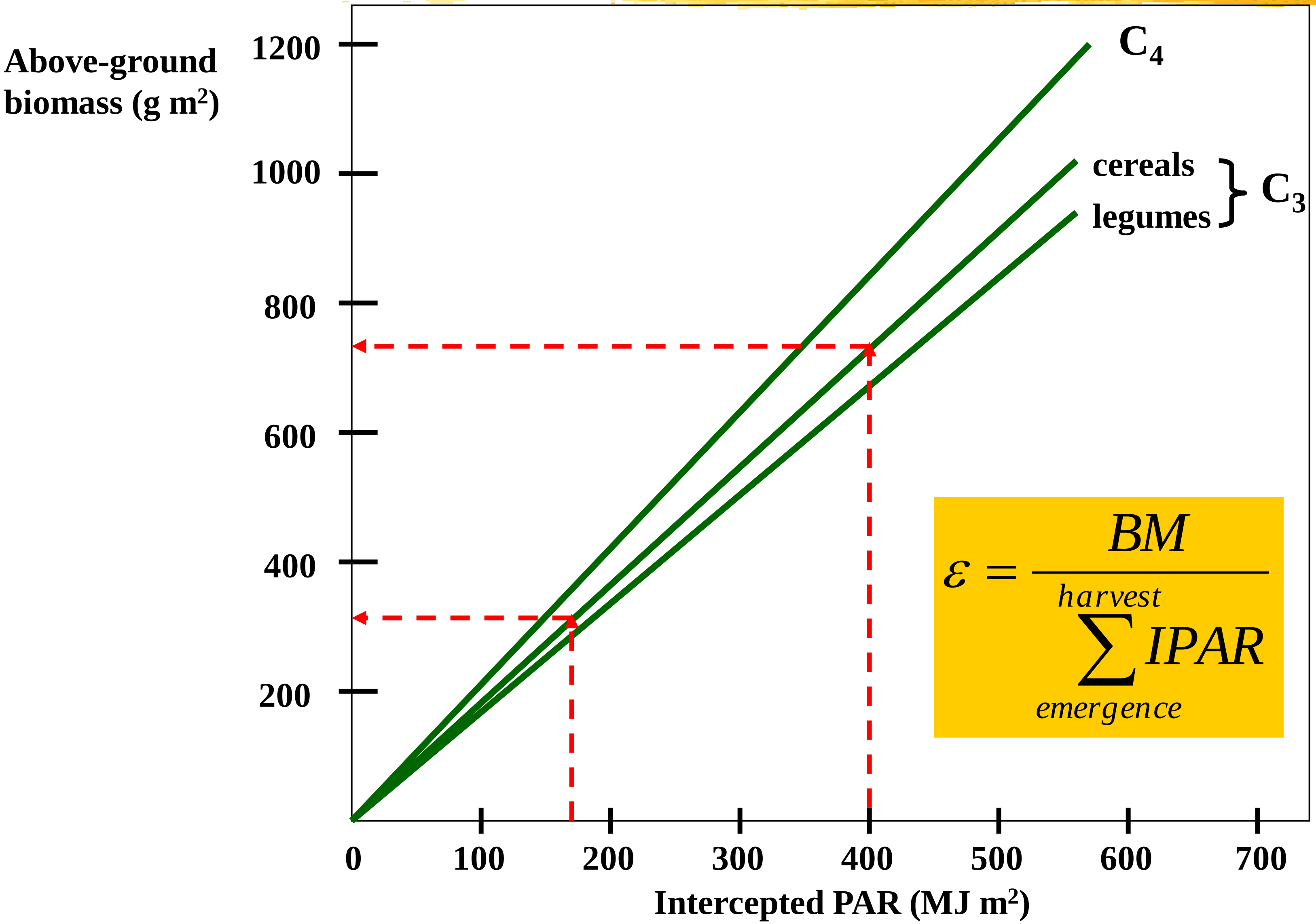
adapted after Jones et al., 1998

CROPSYST approach



Source: Todorovic, 2005

Energy-biomass conversion ratio (ε) or Radiation Use Efficiency (RUE) Concept



$$\varepsilon = \frac{BM}{\sum_{emergence}^{harvest} IPAR}$$

CROPSYST approach

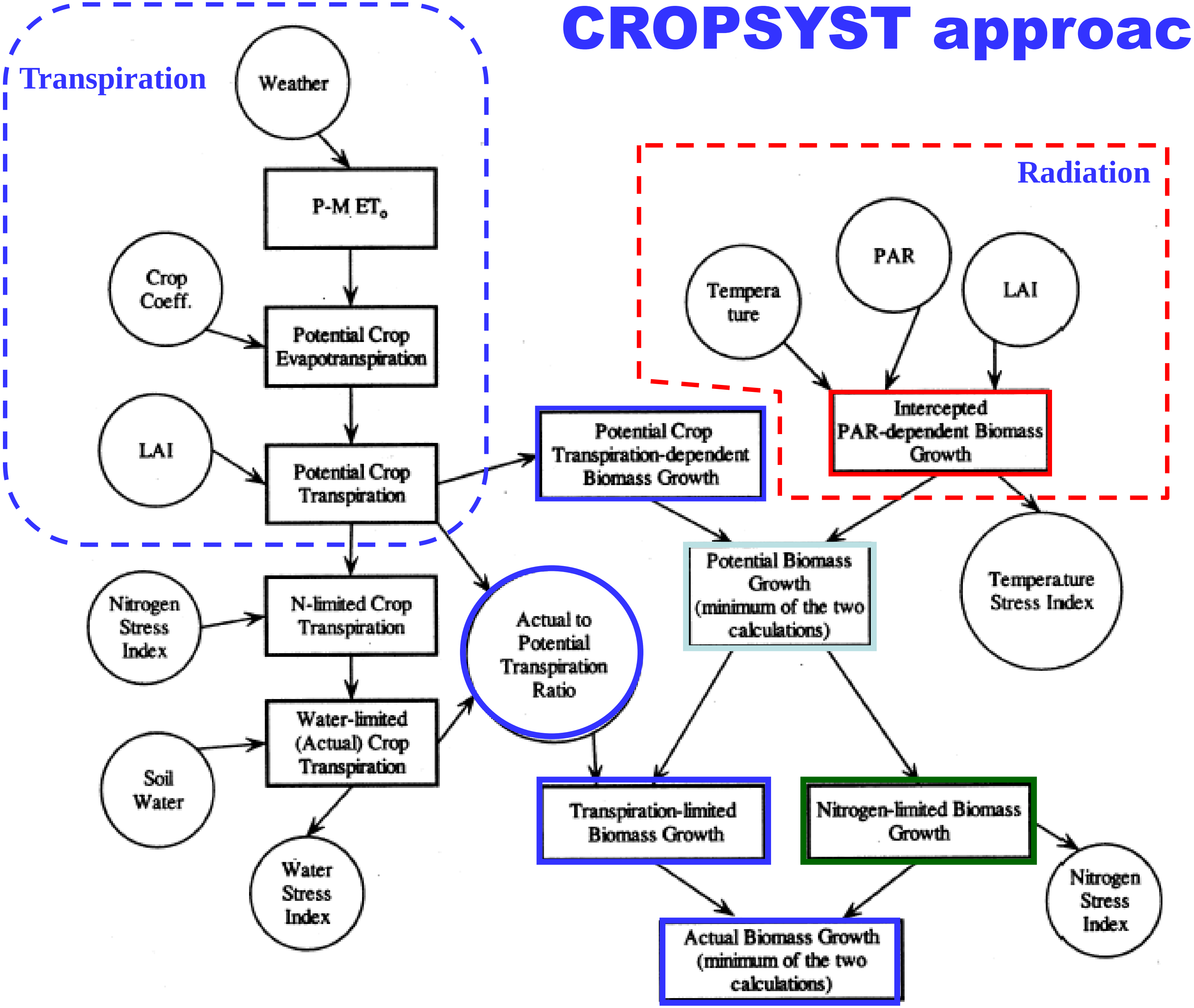


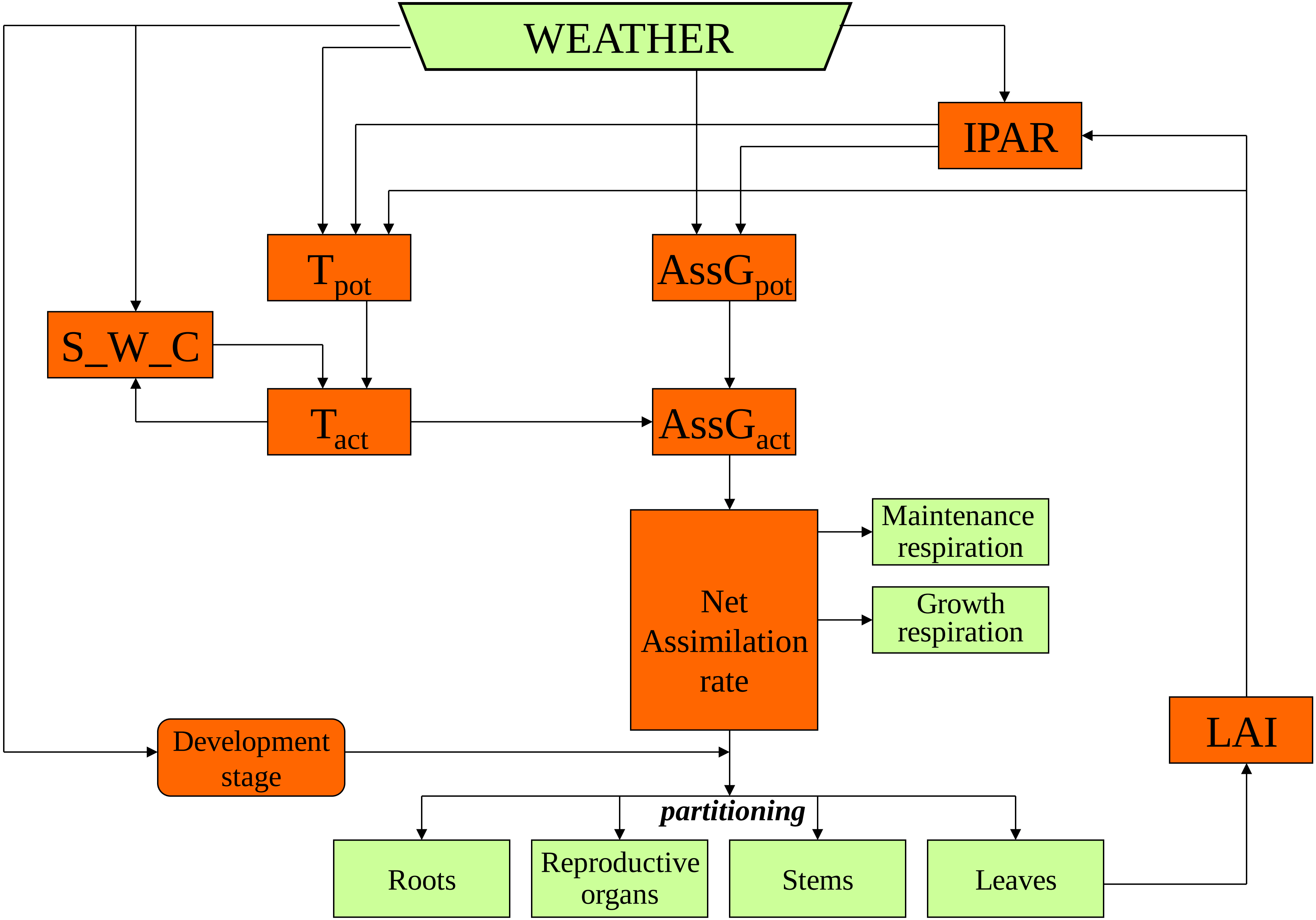
Fig. 1. Flowchart of biomass growth calculations in CropSyst.

Source: Stockle et al., 2003

Crop Growth Modeling – Dutch School (of De Wit)

- 60’ & 70’ … C.T. de Wit
  - Process-research oriented (photosynthesis, transpiration and respiration)
  - ELCROS (Elementary Crop Simulator) … BACROS, PHOTON (second time-step)
- 80’ … SUCROS (Simple and Universal Crop Growth Simulator)
  - Purpose-oriented: studies of climate effects on production and water management
  - Process description are universal and the model is tailored to various crops by altering the crop parameters
  - Wheat, potato, soybean, maize, sugar-beet …
- 90’ … WOFOST (World Food Studies)
  - Application-oriented: land evaluation, regional yield forecasting (MARS project)
  - Wheat, Grain Maize, Barley, Rice, Sugar Beet, Potato, Field Bean, Soybean, Oilseed Rape, Sunflower …
- Other Dutch models:
  - INTERCOM (Interplant Competition) – interaction of weeds and field crops
  - MACROS (Modules of an Annual Crop Simulator), ORYZA – for rice production

WOFOST approach



WEATHER

IPAR

T_{pot}

$AssG_{pot}$

S_W_C

T_{act}

$AssG_{act}$

Net Assimilation rate

Maintenance respiration

Growth respiration

LAI

Development stage

partitioning

Roots

Reproductive organs

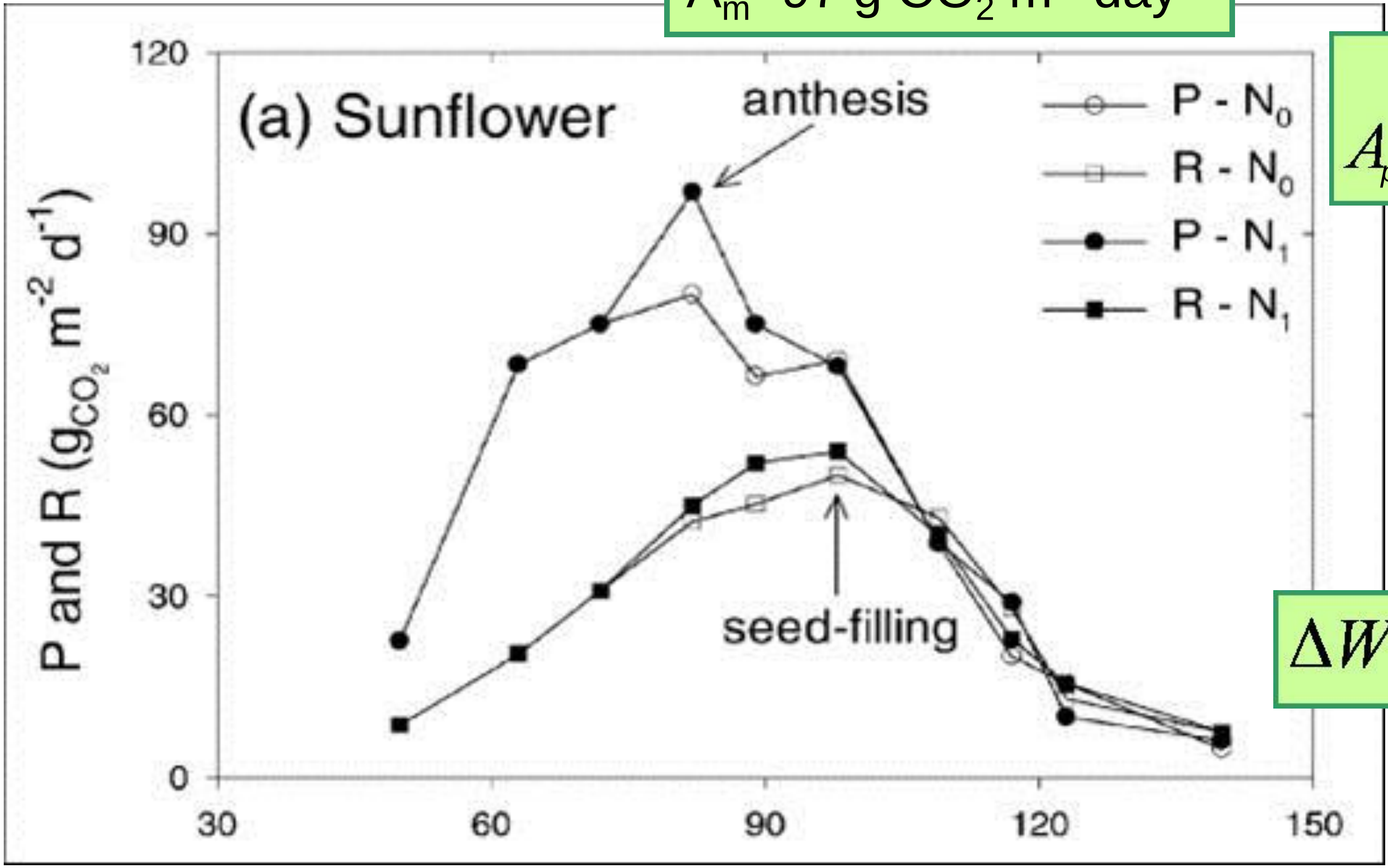
Stems

Leaves

adapted after Kropff and Van Laar, 1993

Maximum gross assimilation rate at light saturation

A_m=97 g CO_2 m^{-2} day^{-1}



Source: Albrizio and Steduto, 2003

$$A_p = A_m \cdot (1 - e^{\frac{-\varepsilon PAR_a}{A_m}})$$

$$A = \frac{T_a}{T_p} \cdot A_p$$

$$\Delta W = C_e \cdot (A - R_m)$$

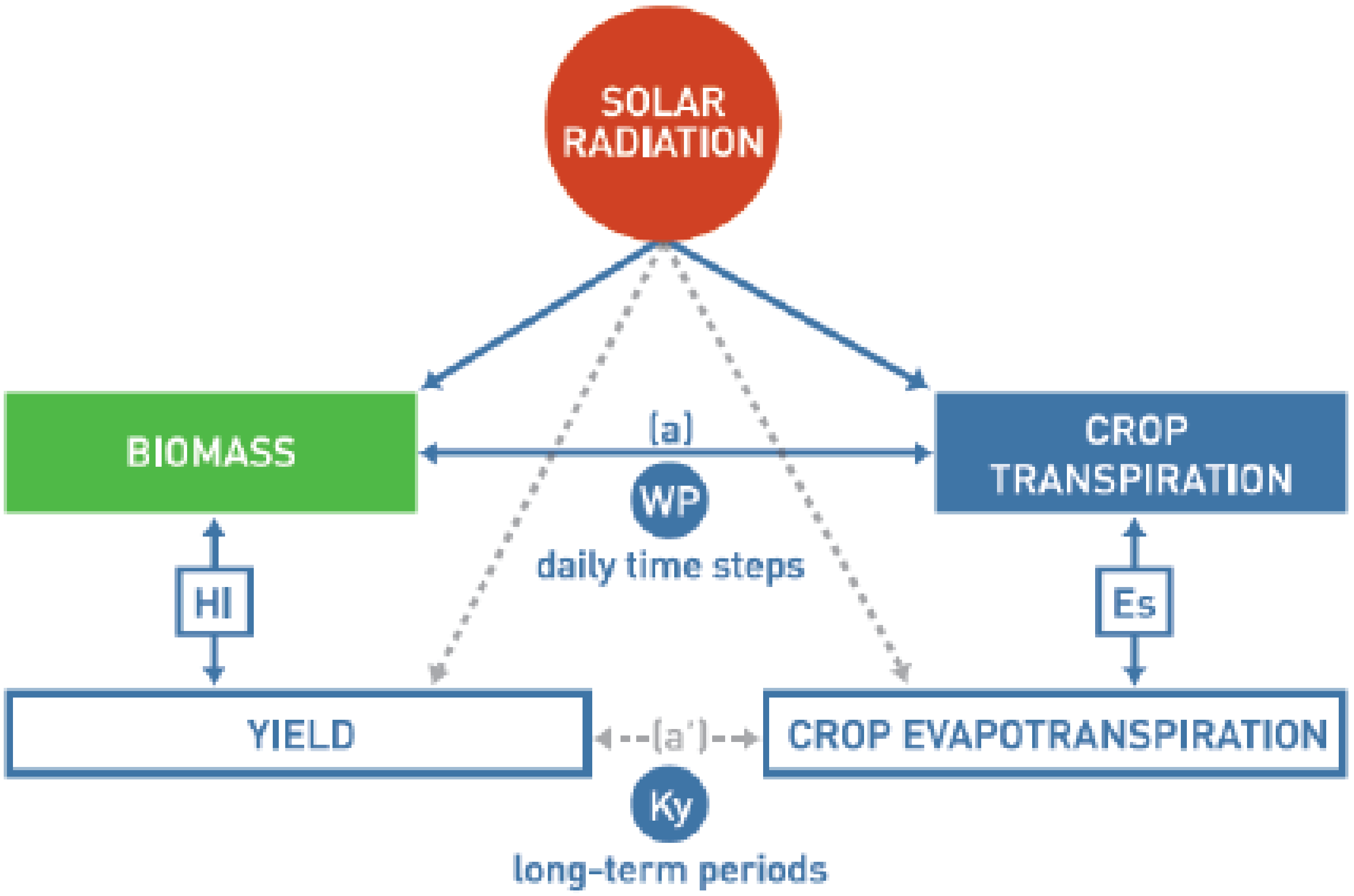
Crop Growth Modeling – Other Schools

- French school (since 1996)
  - STICS (Simulateur multidisciplinaire pour les Cultures Standard) by INRA et al.
  - Interactive modular modeling platform adaptable for various crops through the use of *generic parameters* (relevant for most crops) and *options in model formalization* concerning both eco-physiology and crop management
  - Wheat, maize, soybean, sorghum, grassland, tomato, beetroot, sunflower, pea, rapeseed, banana, sugarcane, carrot, lettuce, …
- Australian School
  - APSIM (Agricultural Production Systems Simulator) by CSIRO
  - Generic modular modeling system based on experiences of CERES, SORKAM and EPIC and composed of biological, environmental and management modules.
  - Maize, wheat, barley, sorghum, millet, sugarcane, sunflower, canola, chickpea, soybean, peanut, fababean, lucerne, cotton, …

Crop Growth Modeling – FAO approach (AQUACROP)

- Peculiarities
  - Water driven growth engine
  - E & T separated using Ritchie approach
  - Decoupled from biomass partitioning
  - Based on canopy ground cover instead of LAI
  - Based on functional root/shoots relations
  - Climate normalization of water productivity (ETo and CO_2)
  - Lowest number of crop parameters in mechanistic dynamic crop growth models
  - Production limitations related to the water availability (water stress and aeration stress), fertilizers applications (soil fertility stress), air temperature (stress) and water quality (salinity stress)

Crop Growth Modeling –
FAO approach (AQUACROP)



Source: Steduto, 2005

AquaCrop approach – water driven growing engine

$$AGB_{dry} = Wp \sum_{i=1}^{N} \left(\frac{T_r}{ET_o}\right)_i$$

AGB_{dry} : Dry Above Ground Biomass [g/m^2]

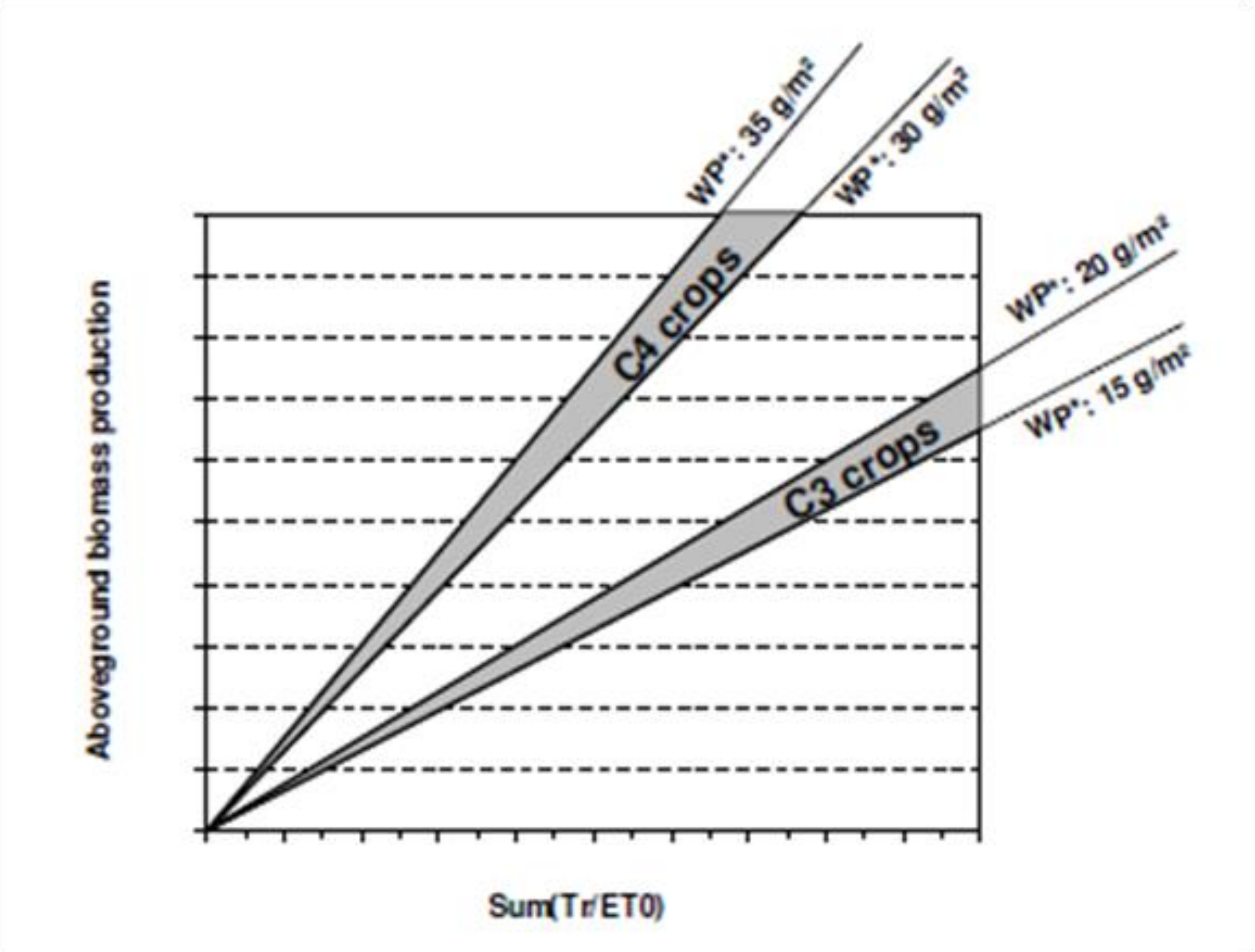
Wp : Crop Water Productivity [g/m^2]

T_r : Crop Transpiration [mm] for each day i of crop growth

ET_o : Reference Evapotranspiration [mm] for each day I of crop growth

N : total number of days of crop growing period

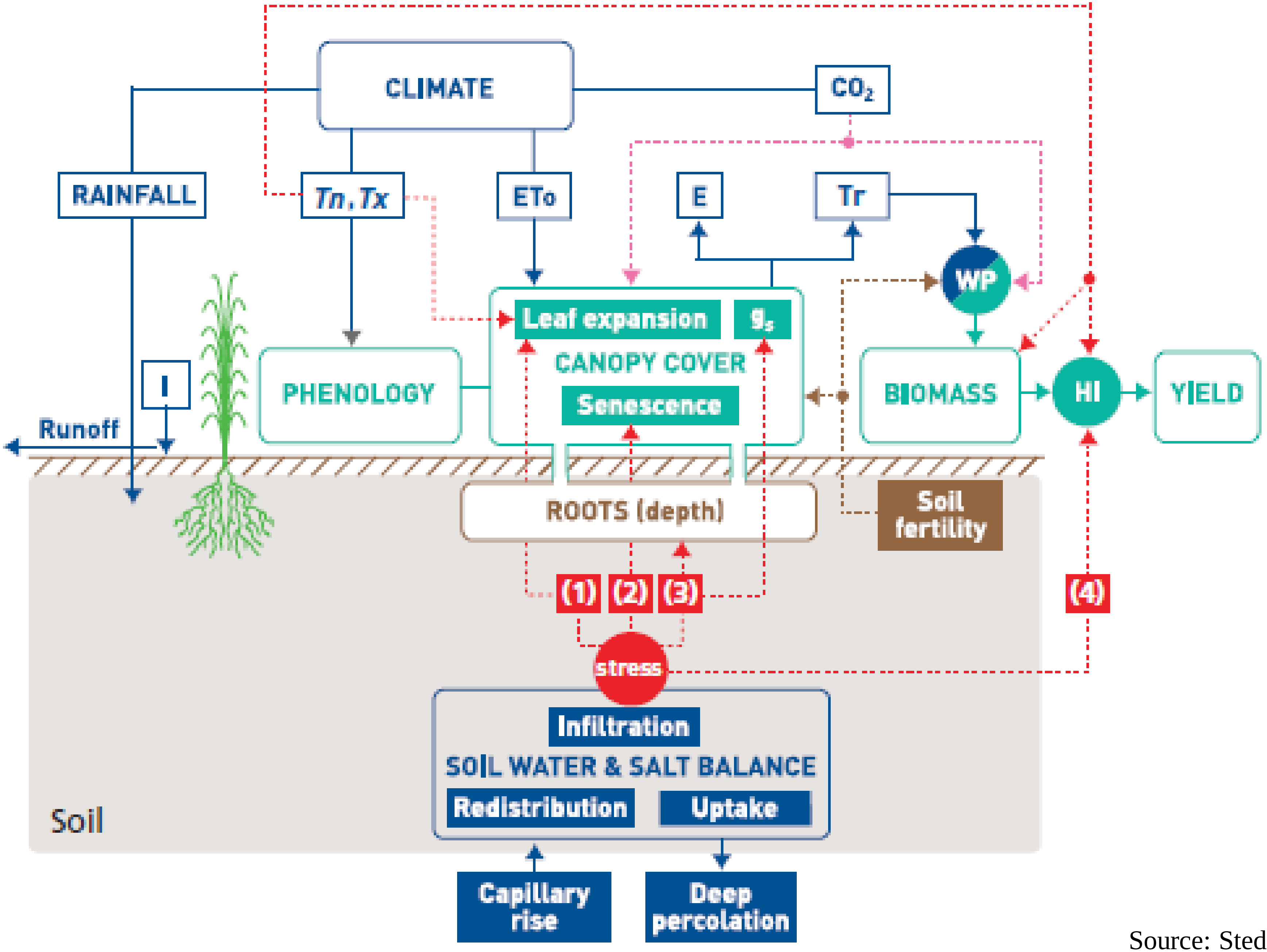
Common range of WP for C3 and C4 crops: The ratio between AGB$_{dry}$ and Tr normalized for ETo



Exercise

- One crop had seasonal evapotranspiration of ETc=400 mm while reference evapotranspiration (ETo) during the growing season was 500 mm. Evaporation losses during the growing season were 25% of crop evapotranspiration. Estimate dry above ground biomass knowing that crop water productivity Wp=15 g/m^2 and growing season duration was 200 days.
- What was the fresh yield of that crop in t/ha if dry above ground biomass represents 10% of fresh biomass and harvest index was 0.5?
- What will be fresh yield of the same crop if crop growing season was reduced, due to air temperature increase, by 10% while all other parameters remained unchanged.

Flowchart of AquaCrop modelling steps indicating the main components of Soil-Plant-Atmosphere Continuum

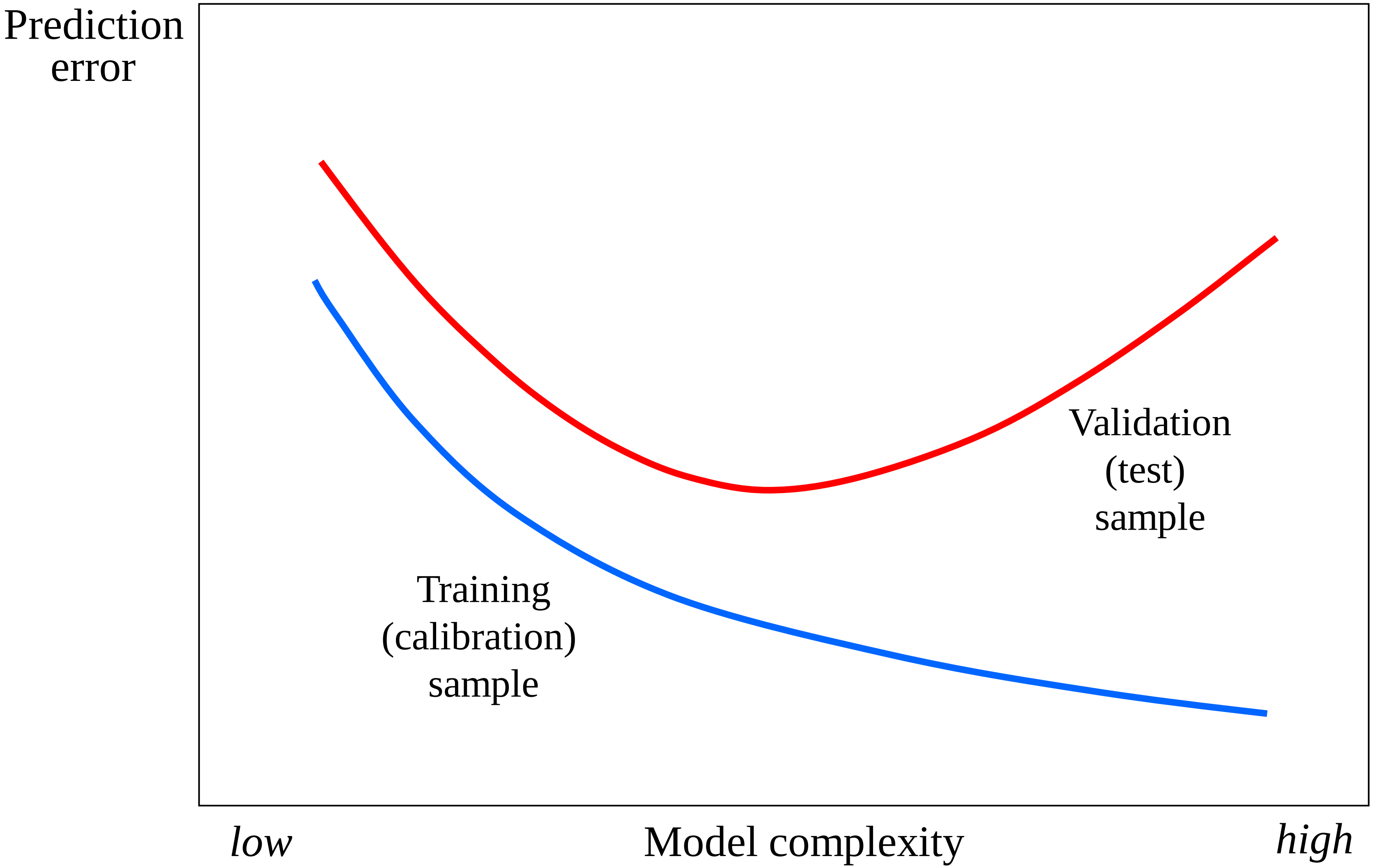


Source: Steduto, 2008

… instead of a synthesis …

- CGM are simplified representation of agricultural systems
- The crop growth engines are:
  - solar radiation (light and temperature),
  - water,
  - nutrients and
  - CO_2
- Carbon driven CGM (e.g. WOFOST)
- Radiation (and ET) driven CGM (e.g. CROPSYST)
- Water (Transpiration) driven CGM (e.g. AQUACROP)

Modeling: Prediction vs. Complexity



Source: anonymous