H2020-TWINN-2015-Serbia for Excell

Agrometeorological modeling - abiotic stress and plant production

Teaching material for PFNS students for improved curricula

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PREFACE

Teaching material "**Agrometeorological modeling - abiotic stress and plant production**" was prepared jointly by participants in the project H2020-TWINN-2015-Serbia for Excell. It is based on the teaching material prepared during specific activities which took place during the project lifetime (2016-2018): expert trainings, scientific visits and guest lectures. The aim of this booklet is to be used as additional teaching material during the following courses at the University of Novi Sad, Faculty of Agriculture:

1st cycle (undergraduate studies, B.Sc. level):

Meteorology, Crop modeling, Plant Physiology, Ecotoxicology and environmental protection, Forage crops in organic agriculture, Growing of cereals and pulses, Growing of industrial plants and Organic field crop production

2nd cycle (M.Sc. level):

Bioremediation, The role of cover crops in organic farming

Parts of this teaching material are implemented already from summer semester 2016/2017 and 2017/2018 in the frame of the course Ecotoxicology and environmental protection both in theoretical part (lectures) and during practical work. The other parts are going to be used from winter semester 2018/2019.

The entire text is published also in Serbian to facilitate implementation on undergradute courses.

Part 1 – (Agro)meteorology, agroclimatic indices and models, agrometeorological measurements and weather forecasting

1.1. Solar radiation: Interaction with vegetation

1.1.1. Physical base

Solar radiation is electromagnetic radiation which may be considered as a flux of photons or as waves. This different definition of electromagnetic radiation is explained by different phenomena related to solar radiation such as the photoelectric effect which find only an explanation if solar radiation is defined as a flux of photons or vice versa optical phenomena such as the glory which is related to wave interference. The main characteristic of electromagnetic radiation is however its wavelength (Fig. 1.1). The electromagnetic spectrum extends from very short wavelengths (Gamma rays) in the order of magnitude of 10-4 µm to very long wavelengths in the order of magnitude of cm. Each photon has an own energy el which depends on the wavelength of the photon according to the following equation

$$e_l = hn = h\ c/\lambda \qquad (1.1)$$

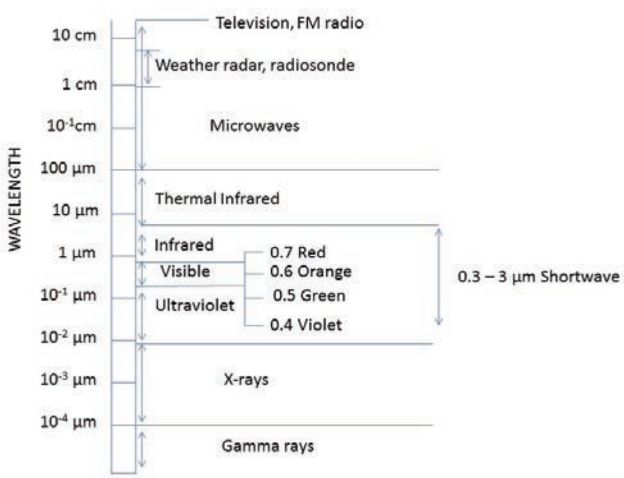


Figure 1.1 Overview of the different wavelength ranges of electromagnetic radiation

where h is the Planck constant (6.626 10^{-34} J·s), n is the frequency of the light in Hz, c is the speed of light (3.10^8m/s) and l is the wavelength in meter.

According to this equation the energy of one photon becomes larger when the wavelength decreases and becomes smaller for larger wavelengths. The wavelength ranges of interest in meteorology span from the ultraviolet (UV) wavelength range (starting at about 0.2µm) to thermal infrared (IR) wavelength ranges which ends at 100µm. This domain is divided in two parts in the short wavelength range between 0.3 and 3 µm where almost all the radiation is emitted by the sun and the long thermal IR wavelength range between 3 and 100µm where all colder (temperature below 100 °C) objects and gases emit radiation. The lower part of the solar spectrum below 0.4µm is called the UV wavelength range and is subdivided in the UV-C wavelength range below 0.28µm, in the UV-B wavelength range between 0.28µm and 0.32 µm and the UV-A range between 0.32 and 0.4µm. Solar radiation in the UV-C wavelength range is completely absorbed by the oxygen molecules and by ozone in the atmosphere and does not reach the ground. UV-B is compared to UV-A more harmful because of the lower wavelength and the higher photon energy. The visible radiation of the electromagnetic spectrum (that is visible to the human eye) refers to the wavelength range between 400 and 800nm.

Photons in the short wavelengths ranges (e.g. UV) are more energetic and have therefore a higher biological efficiency. UV radiation is among other things known for its damaging impact on the biosphere (plants, humans and animals). For humans, UV radiation leads to acute negative effects on health such as sun burn or may also lead to long-term effects such as skin cancer which result from a high UV exposure during the whole life. The total energy from electromagnetic waves E is determined by calculating the inte-

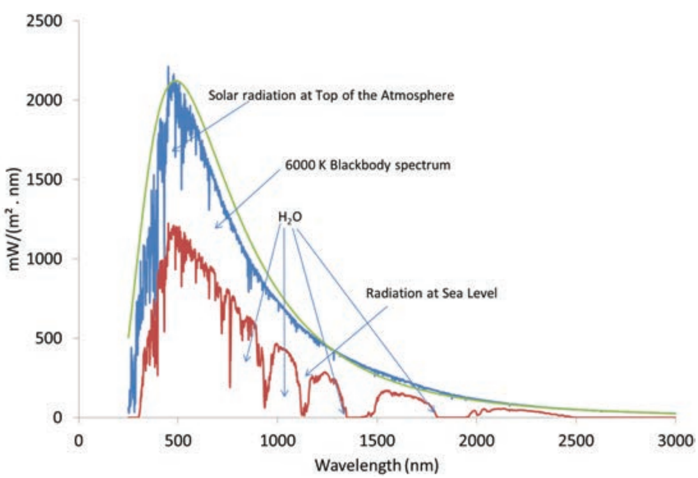


Figure 1.2 The solar spectrum for cloudless conditions is shown at the top of the atmosphere (blue line) and at ground (red line). The reduction of solar radiation between top of atmosphere and ground is caused by scattering by air molecules, absorption and scattering by aerosols and absorbtion by atmospheric gases such as water vapour. Simulations were performed with the LIBRADTRAN software package. www.libradtran.org. (Mayer and Kylling, 2005)

gral over the given wavelength range of the photon energy multiplied with the number of photons following equation (1.2):

$$E = \int_{\lambda 1}^{\lambda 2} e\,\lambda\, n_{\lambda}\; d\lambda \qquad (1.2)$$

where n_{λ} is the number of photons at the wavelength λ, e_{λ} represents the energy of a photon with a wavelength λ, λ is the wavelength.

Since the number of photons in the UV wavelength range is lower, the total sun energy will be higher at larger wavelength ranges. Fig. 1.2 shows the distribution of the solar energy along the spectral range of the sun.

1.1.2. Physiological effects of radiation on plants

1.1.2.1. UV radiation

Physiological effects of UV radiation on plants

As already mentioned photons in the short wavelengths ranges (e.g. UV) are more energetic and have therefore a higher biological efficiency. Figure 1.3 shows the spectrum of the plant damage and the DNA and plant damage weighting functions. They display a strong increase with decreasing wavelengths. In order to obtain the UV doserate the weighting functions need to be multiplied with the solar spectrum and integrated over the whole wavelength range. The effects of exposure to UV-B radiation on various physiological processes in plants may be subdivided in 4 different types of effects (Prasad et al., 2003):

1) Damages on the plant. These damages consist of damages of the DNA, degradation of the proteins in the plant tissue and fatty acid destruction. UV-B damaging effects on plants include the destruction of the cell membranes and all organelles within the cell, including mitochondria, chloroplasts, and deoxyribose nucleic acid (DNA) within the nucleus.

2) These damages to the cell organelles in turn influence the metabolic processes of the plant such as photosynthesis, respiration, growth and reproduction and eventually impact crop yield and quality. UV-B leads to strong morphological changes in plants. Leaves that are exposed to enhanced UV-B radiation first develop irregular chlorotic patches. With a continuation of exposure to UV-B, the chlorotic patches turn to brown necrotic spots before they later die. Other effects of UV-B are: reduction of the plant height, decrease in individual leaf size, reduction of branch length and decrease of tiller number. These morphological changes also lead to a reduction of the density of the canopy. A less dense canopy in turn

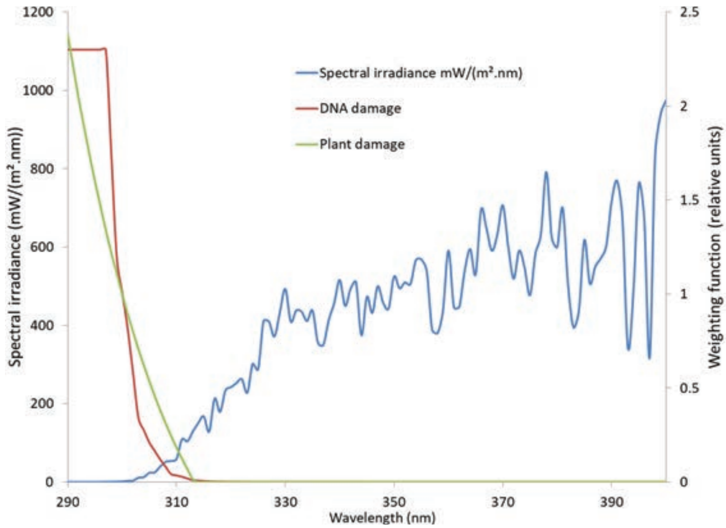


Figure 1.3 Solar spectral intensity compared with the DNA damage and the plant damage weighting functions. Simulations were performed with the Fast RT online tool (https://fastrt.nilu.no/) (Engelsen and Kylling, 2005)

intercepts less UV-B radiation than a plant grown under favorable conditions.

3) Reduction of reproduction. In general, the reproductive organs of most plants are highly protected. Sepals, petals, and ovary walls "screen" the reproductive organs from UV-B. Pollen is therefore "at risk" when it falls on the stigma. Then rate of pollen tube growth and pollen germination are in turn affected by UV-B radiation. A decrease in pollen tube growth by 10-25% may result. The fertilization process of sensitive plants is affected too, resulting in fewer seeds in these plants. However, the walls of the style and ovary may provide some protection once the pollen tube has penetrated the stigma.

4) Strategies for protection against UV-B radiation: During the process of evolution, plants developed repair and defense mechanisms by which UV-B damages to the cell are limited and tolerance to solar UV-radiation is increased. Several UV-driven repair and defense mechanisms exist, which modify the optical characteristics of the leaves or other parts of the plant, or which work at the biochemical-molecular level. Cellular life forms usually possess repair enzymes that can recognize chemically modified bases, including those formed by UV radiation. In addition, a variety of biochemical mechanisms exist to restore the integrity of the genetic material after DNA damage, and thus to maintain its stability.

The first kind of defense mechanism is based on a better adaptation of the surface structure, physiology, and composition of the epidermal layer to attenuate the transmission of UV-B through the epidermal layers, and eventually to better shield cells from UV-B radiation. The protective structures have the capacity to attenuate radiation damage by reflecting, absorbing, and scattering the incident flux. Among other mechanisms, hairs and wax coating have a prominent role. UV-B radiation leads to oxidative stress in plant systems, similarly to what is observed for abiotic and biotic stress. As a result, plants increase production of some chemicals such as flavonoids and antioxidant enzymes, which provide defense against UV-B radiation. Flavonoids, which are produced and mostly deposited in leaf hairs and in epidermal and mesophyll layers, are very efficient in mitigating the effects of UV-B radiation. Therefore, flavonoids may reduce damage to sensitive cell organs (e.g., DNA, chloroplasts, and mitochondria). Other compounds that could have the potential to protect against UV radiation effects are carotenoids and anthocyanins. They can protect the pollen grains, especially in flowers. They do not directly influence photosynthesis and other physiological processes, since they attenuate incoming radiation only in the UV-B spectral range and not in the range of photosynthetic active radiation.

The decrease in chlorophyll pigments and photosynthesis usually results in lower biomass and yield of crop plants. Some genotypes of crop species show a thicker leaf wax layer, a loss of chlorophyll, and an increase in phenolics (that allow a better UV-B protection), ultimately resulting in changes in biomass and yield. The effects of UV-B on yield vary very much with crop species, however. In any case, most of the studies show that UV-B increases lead to yield loss (Table 1.1).

Crop	Simulation of O_3 depletion (%)	Experimental condition	Observed change in yield (%)
Barley	-	F	−17 to −31
Black gram	−15	F	−63
Corn	−20	F	−22 to −33
Mung bean	−15	F	−76
Soybean	−16	F, GH	−41
Wheat	−12, −20, −25	F	−43
	15	F	15

Table 1.1 Selected results quantifying the influence of increased UV radiation on crop yield. *F* outdoor experiments, *GH* Greenhouse experiment
Source: Kakani et al.(2003)

Some species such as millet (*Setaria italica*), cowpea (*Vigna unguiculata*) and tobacco (*Nicotiana tabacum*) show nearly no yield reduction. Other species (e.g., pea, barley (*Hordeum vulgare*), mustard (*Brassica nigra*), Black gram, Mung bean, and wheat) show a strong reduction (Table 1.2). This yield loss consists of a reduced fruit grain number due to failure in fertilization, destruction of fruiting structures, and reduced fruit size due to decreased supply of assimilates to the growing sink (fruits). UV-B also affects the yield quality. For instance, protein content and seed oil are reduced in soybeans that are exposed to enhanced UV-B radiation.

Table 1.2 Sensitivity of selected crops to enhanced levels of UV-B radiation. Results of experiments performed in controlled environments. *Source*: Prasad et al. (2003)

Sensitive	**Moderately sensitive**	**Relatively tolerant**
Barley (*Hordeum vulgare*)	Common bean (*Phaseolus* spp.)	Corn (*Zea mays*)
Carrot (*Daucus carota*)	Lettuce (*Lactuca sativa*)	Cotton (*Gossyptum hirsutum*)
Cucumber (*Cucurnis sativus*)	Peanut (*Arachis hypogaea*)	Cowpea (*Vigna unguiculata*)
Mustard (*Brassica* spp.)	Pepper (*Piper nigrum*)	Clover (*Trifolium* spp.)
Oats (*Avena sativa*)	Petunia (*Petunia* spp.)	Millet (*Setaria italica*)
Pea (*Pisum sativum*)	Potato (*Solanum tuberosum*)	Radish (*Raphanus sativus*)
Soybean (*Glycine max*)	Rice (*Oryza sativa*)	Sunflower (*Helianthus annuus*)
Sweet corn (*Zea mays* var. *saccharata*)	Rye (*Secale cereale*)	Tobacco (*Nicotiana tabacum*)
Tomato (*Lycopersicon* spp.)	Sorghum (*Sorghum vulgare*)	Wheat (*Triticum aestivum*)

Factors influencing UV radiation

Ultraviolet radiation shows diurnal as well yearly variations (Figure 1.4). The intensity of the incident UV irradiance at the ground depends on 5 meteorological parameters.

- the solar elevation. The solar elevation first directly influences the length of the optical path of the sun rays through the atmosphere. The longer the optical path the larger the extinction (reduction) of solar radiation. Second, the angle of incidence of the solar rays on the ground has an influence on the direct irradiance on the horizontal. Following the Lambert-Bouguer law which states that the received direct beam irradiance I equals the irradiance of the direct beam on plane perpendicular to the sun rays I0 multiplied with the cosine of the solar zenith angle (sza).

$$I = I0 \cos(sza) \qquad (1.3)$$

The lower the solar elevation (the larger the sza) the lower the intensity of the direct beam radiation on a horizontal plane will be.

- cloudiness: clouds reflect the incident radiation and lead to a strong reduction of the solar irradiance. Cloudiness is one of the main factors leading to strong day to day variations of the daily sum of solar radiation (Fig. 1.4).
- column ozone: Solar radiation in the UV wavelength region is filtered by ozone which absorbs ozone. Column ozone which is the integral of the ozone over the whole atmos-

pheric column therefore directly affects the intensity of UV radiation at the ground (Fig. 1.5).

- aerosol concentration in the atmosphere: aerosol are small liquid or solid particles in the atmosphere which have natural and anthropogenic sources. The higher the aerosol concentration the higher the solar UV reduction. The magnitude of aerosols on UV intensity is however compared to cloudiness and ozone much lower but may still reach 30%.
- ground reflection (albedo): ground reflected radiation may first lead to an increase of the UV dose received by an object through direct reflection from the ground to the object. Second the ground reflected radiation may be scattered by the atmosphere back to the ground. The higher the ground albedo the higher the back scattering by the atmosphere will be.

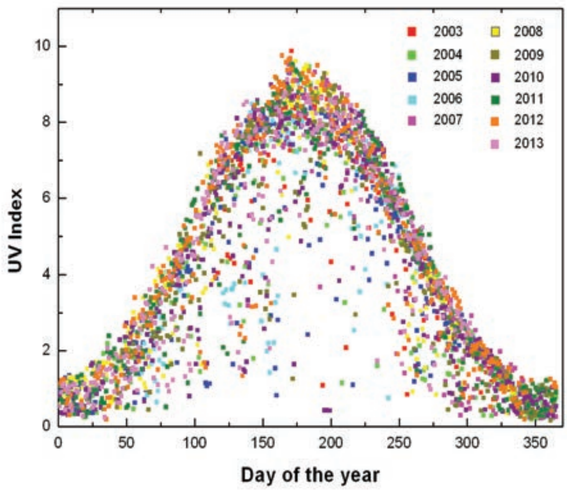


Figure 1.4 Yearly variations of daily UV index (maximum UV index) for Novi Sad, Serbia The UV index is a weighted and homogenized quantity which quantifies the intensity of erythemal UV radiation. Source: (Mijatovic et al., 2014)

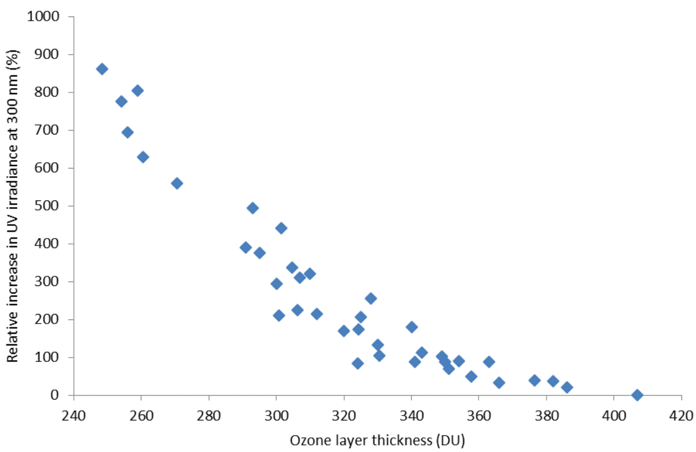


Figure 1.5 Relative increase in UV radiation at 300nm as a function of ozone layer thickness. The relative increase in UV irradiance is referred to the UV irradiance at 420 Dobson Units (D.U). The measurements were performed by BOKU at Sonnblick Observatory.

1.1.2.2. Physiological effects of visible radiation on plants

During photosynthesis light energy is converted by plants and other organisms into chemical energy that can later be released to drive the organisms' activities (energy transformation). This chemical energy is stored in the plant. In most cases, oxygen is also emitted as a waste product. Photosynthesis is an essential physiological process for most plants, algae, and cyanobacteria and the production of the oxygen content of the Earth's atmosphere is directly related to it. Organic compounds and most of the energy necessary for life on Earth are also provided by this physiological process.

Photosynthesis always begins when energy from light is absorbed by proteins which contain green chlorophyll pigments. In plants, these proteins are embedded in organelles called chloroplasts, which are most abundant in leaf cells, while in bacteria they are held inside the plasma membrane. In these light-dependent reactions, oxygen gas is produced.

The light which is used for the photosynthesis is called photosynthetic active radiation (PAR).

PAR refers to the integral of radiation between 0.4 and 0.7 µm. Photons at shorter wavelengths tend to be so energetic that they can be damaging to cells and tissues. They are however mostly absorbed by the ozone layer in the stratosphere. Photons at longer wavelengths do not hold enough energy to allow photosynthesis to take place.

1.1.3. Solar radiation in a canopy

Crops grow and use water using intercepted radiation from the sun, and the atmosphere. Diurnal changes of solar radiation trigger the diurnal course of photosynthesis and transpiration, and the vertical gradient of solar radiation in a canopy is a measure of the absorption of energy by the canopy at different heights.

The transfer of radiation is rather complex: solar radiation above the canopy consists of direct and diffuse radiation. This radiation undergoes various events in the canopy (Fig. 1.6) :

1) Reflection by leaves and by stems (photons are bounced back)
2) Scattering by the air: the photons change direction without energy transformation. Scattering is especially visible when small droplets scatter direct sun light towards the observer.
3) Absorption: Solar radiation may be absorbed by leaves, stems or by the ground. The radiation energy is transformed into heat or chemical energy (e.g. for photosynthesis)

4) Transmission: the transmitted solar radiation is the solar radiation which comes through to a certain height in the canopy. We distinguish between directly transmitted radiation (direct solar beam comes to the ground) and transmitted diffuse radiation (diffuse sky radiation, reflected or scattered radiation which arrives to a given point). The inhomogeneities in leaf distribution (Fig. 1.7-1.9) result in an inhomogeneous radiation distribution at the ground with points with maximum solar radiation intensities where direct beam radiation reaches the ground (which are called sunflecks Fig. 1.8b) and darker areas where only diffuse and indirect radiation comes through (Fig. 1.6).

Figure 1.6 Radiation field in a forest. The distribution of incoming solar radiation at the ground is very inhomogeneous due to shading effects. This leads to local intensity maximum of solar radiation at the ground called "sun flecks".

1.1.3.1. Investigation methods of radiative transfer in a canopy

A classical method to investigate solar radiation in a canopy is by using a camera with a fish eye lense (Fig. 1.7-1.9). The fish eye camera photographs show the whole upper hemisphere. Using a special software which digitalizes the photograph it is possible to determine the fraction of visible sky, to calculate the leaf area index (Software Hemiview https://www.delta-t.co.uk/product/hemiview/) which is a quantity/parameter which characterizes the density of a canopy. In turn the transmitted direct and diffuse solar radiation may be determined (Figure 1.8). Figure 1.7 a-c show 3 different fish eye photographs taken before during and after fall of leaves (22. October to 15. December 2016) in the garden of BOKU.

Figure 1.7a Fish eye photograph taken on the 31. October 2016 in the biological garden of Universität für Bodenkultur.

Figure 1.7b Digitalization of the fish eye photograph to determine the partition of visible sky on the photograph. 44 % of the sky is visible.

Figure 1.8a Fish eye photograph taken on the 14. November 2016 in the biological garden of Universität für Bodenkultur. 47 % of the sky is visible

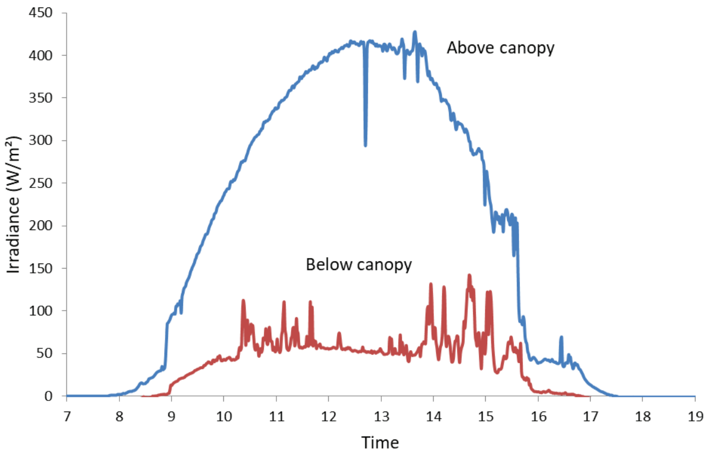


Figure 1.8b Solar radiation above and below the canopy on 13. November 2016. The radiation at the ground shows maximum intensities (sun flecks) as soon as the direct beam comes through the canopy.

Figure 1.9a Fish eye photograph taken on the 25. November 2016 in the biological garden of Universität für Bodenkultur.

Figure 1.9b Digitalization of the fish eye photograph to determine the partition of visible sky on the photograph. 49 % of the sky is visible.

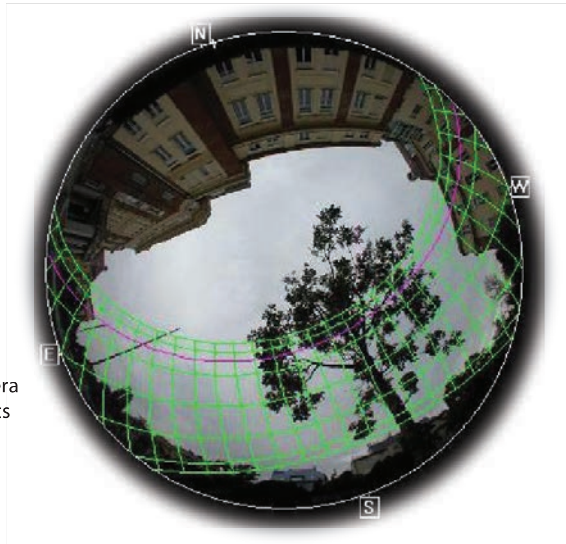


Figure 1.10 Analysis of a fish eye camera photograph. Layering of the sun orbits on the photographs is used to determine time of the days where sensor/observer is shaded. Source (Kerestes, 2016)

Figure 1.11 Instrumentation for measuring shortwave and longwave radiation balance in a canopy. A four component radiometer measures separately with 4 different optical sensors downward shortwave and longwave and upward shortwave and longwave radiation data are automatically stored using a datalogger which is installed in the bucket.

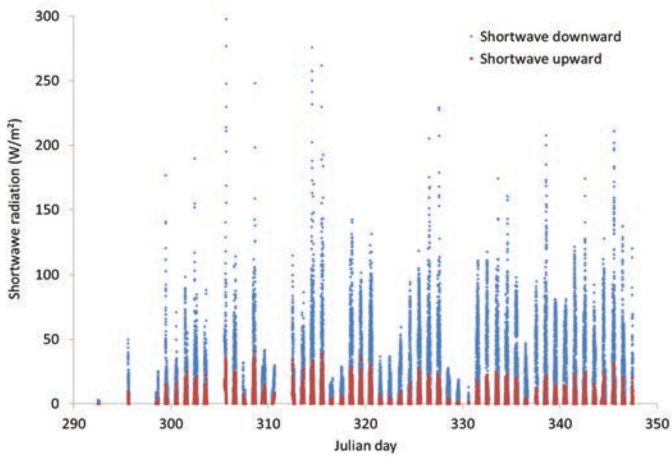


Figure 1.12 Measured shortwave downward (blue line) and upward radiation (red line) at BOKU garden during the measuring period 27. October to 13. December 2016

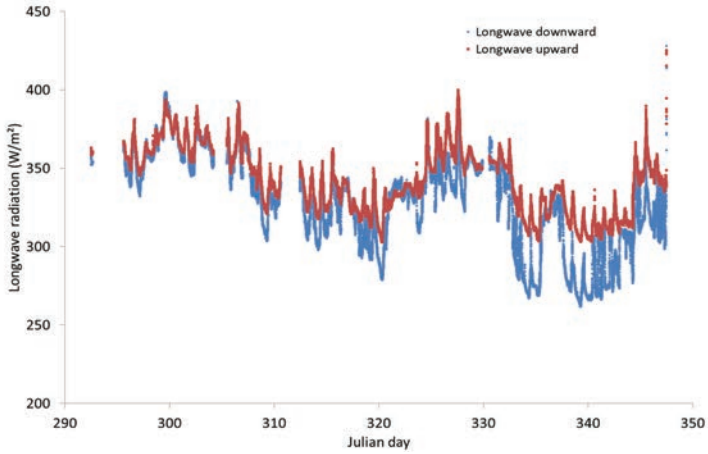


Figure 1.13 Measured longwave downward (blue line) and upward (red line) radiation at BOKU garden during the measuring period 27. October to 13. December 2016. The upward trend is due to the decreasing temperatures towards the end of the year. The decrease is however stronger for the downward longwave radiation because of the fall of the leaves, that have a stronger emission compared to background sky.

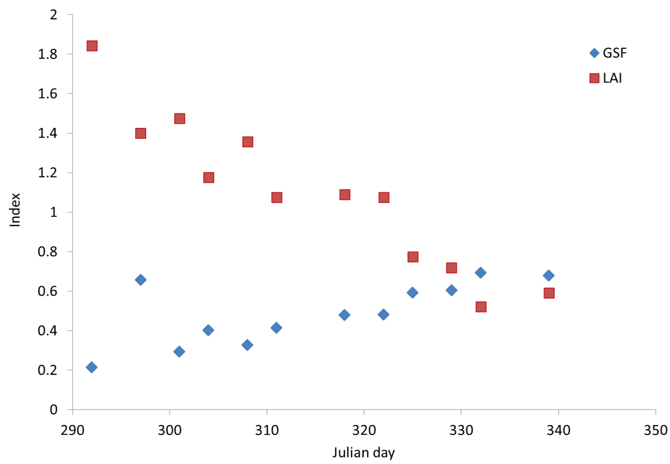


Figure 1.14 Change in LAI and Global Site Factor at BOKU garden during the measuring period. Global Site Factor is the ratio of the radiation below the canopy to the radiation above the canopy

The radiation was measured during the time period 22. October to 13 December 2016 using a Kipp and Zonen 4 component radiometer which measured at a height of 1.5 m above the ground incident downward short and longwave radiation and upward reflected shortwave and emitted longwave radiation (Figure 1.9). The measured shortwave and longwave radiation during this time period are shown in Figure 1.10 and 1.11. Shortwave downward radiation at the bottom of the canopy decreases due to a decreasing sun elevation towards the end of the year. The red curve shows the reflected radiation which is directly correlated to the incident radiation. Figure 1.11 shows the measured downward and upward longwave (LW) radiation. Both show a negative trend with time since the emission of LW radiation by the atmosphere and by the ground are directly correlated to ground and air temperatures which decrease towards the end of the year. The decrease of the downward LW radiation is however stronger than the upward LW because of the increasing proportion of visible sky towards winter time. The sky emits less LW radiation than leaves and trees that have a higher temperature than the sky.

Figure 1.12 shows the change in LAI (ratio area of leaves to surface of the ground below the canopy) and GSF (ratio of radiation below canopy to radiation above canopy) during this time period. The LAI shows as expected a decrease with time due to fall of leaves and the GSF shows an increase due to the reduction of foliage.

1.1.3.2. Model simulations of solar radiation in a canopy

The radiation in a canopy depends on the structure of the canopy (LAI, height of canopy, inclination of leaves, reflectance of stems, type of trees) and on the reflectance of the single leaves. The reflectance transmittance and absorbance by a single leaf is shown

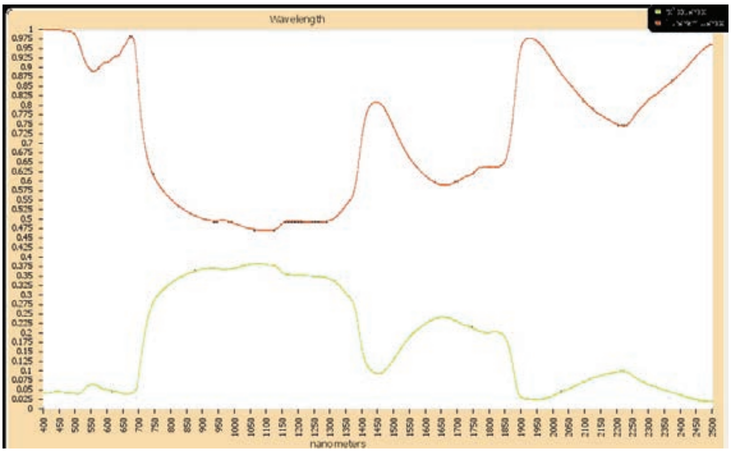


Figure 1.15 Spectral transmittance (red curve) and reflectance (yellow curve) of a leaf. The remaining area is related to the spectral absorption of the incoming solar energy by the leaf. Simulations were performed with an online calculator of leaf properties (OPTICLEAF) http://opticleaf.ipgp.fr/index.php?page=run_prospect (Jacquemoud and Baret, 1990)

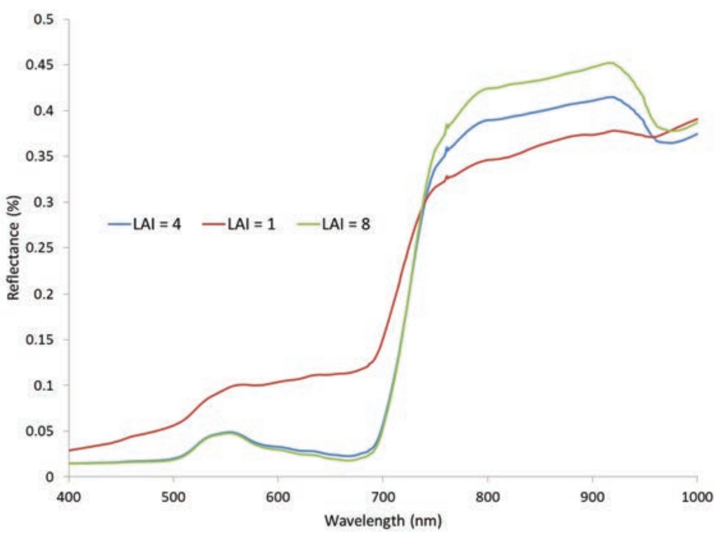


Figure 1.16 Simulation of the spectral reflectance of a canopy as a function of leaf area index (LAI). Simulations were performed with the software Fluormodgui (Zarco-Tejada et al., 2006)

in fig. 15. The reflectance and the transmittance show a maximum in the near infrared (NIR) (0.7 - 1.2 µm) wavelength range with a reflectance around 40% and a transmittance in the same order of magnitude. Another maximum may be seen at 0.55µm (green spectral radiation). Simulations with a canopy and leaf reflectance model show that an increase of LAI leads to an increase in NIR (Fig. 1.16)

1.1.3.3. Thermal longwave radiation in a canopy

Thermal LW radiation is emitted radiation which following the stefan boltzman law depends on the temperature of the emitting object. The emission of a leaf depends on the leaf temperature which depends on the energy balance of the leaf (Figure 1.17). The leaf receives shortwave direct and diffuse energy from the sun and from scattering by the atmosphere as well as reflected shortwave radiation from the surroundings. It reflects or transmits one part of the incident shortwave radiation the other part is absorbed and transformed into heat or chemical energy. Longwave radiation is emitted by the sky and by the surroundings and received by the leaves which absorb the non reflected part of the incident longwave radiation. The leaves also emit LW radiation as a function of their temperature. Energy fluxes between the leaf and the air also include latent and sensible heat exchange. Sensible heat exchange occurs through turbulent heat exchange and depends mainly on the temperature difference between leaf and air. Usually during the day leaves are often warmer than the air, and cooler than the air during the night. Latent heat exchange occurs due to the transpiration of the plants by which water vapour is released to the atmosphere through the stomatas. This latent heat exchange leads to evaporative cooling on the surface of the leaves. As an example, this leads to lower temperature of vegetation compared to sealed surfaces during the day (Figure 1.18a and b).

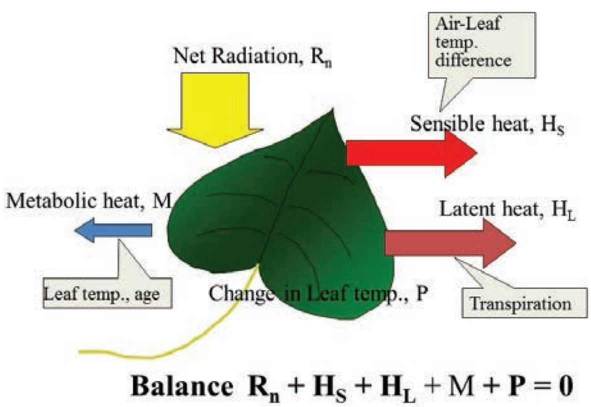


Figure 1.17 Energy balance of a leaf consists of shortwave and longwave radiation (Rn), sensible heat (Hs), latent heat (H_L) and metabolism (M) which is however negligible. P is the change in energy which leads to a change in leaf temperature.

During drought stress the plants close their stomata. The closing of the stomatas leads to a strong reduction of the transpiration of the plant and in turn leads to a higher leaf temperature.

1.1.4. Remote sensing of vegetation

Remote sensing is defined as the acquisition of information about an object or phenomenon without any physical contact with the object. It is therefore in contrast to on-site observation. In agriculture remote sensing is mainly used to obtain information about plant status, plant growth and plant density.

Three methods used in vegetation remote sensing are

1) Methods based on thermal infrared
2) Methods based on spectral reflectance measurements of vegetation
3) Methods based on the chlorophyll fluorescence measurements

A thorough overview of indices and methods used in remote sensing would go far beyond the scope of the present script. In the following sections only some chosen methods will be explained.

a)

b)

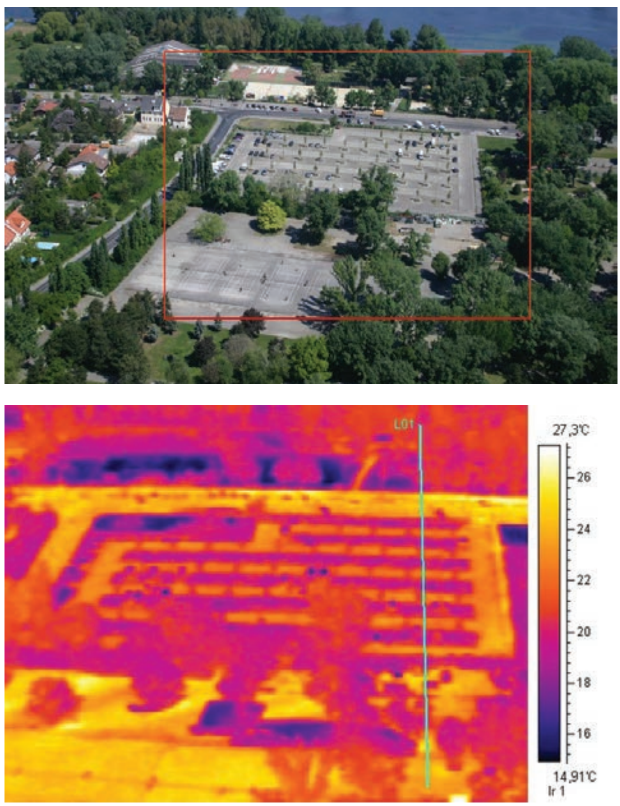


Figure 1.18 Visible photograph (a) of area for which thermal camera photograph (b) was taken. On the visible photograph the area for which temperature was measured with the thermal camera (red rectangle) is indicated. In general, the vegetation surface areas are much colder than the sealed surfaces. Measurements were performed from Donauturm tower in Vienna (provided by Trimmel and Mursch, 2010)

1.1.4.1. *Methods based on thermal infrared measurements*

To determine the drought stress of a plant one widely used method in precision farming is based on measurements of the leaf temperature. One well known index is the Crop Water Stress Index (CWSI)

$$CWSI = (dT - dTi) / (dTu - dTi) \quad (1.4)$$

where
dT is the measured difference between crop canopy temperature and air temperature
dTu is the upper limit of canopy minus air temperature for non transpiring crops
and
dTi is the lower limit of canopy minus air temperature (when crops are well watered)

1.1.4.2. *Remote sensing based on measurements of the spectral reflectance of vegetation*

As already mentioned vegetation has higher reflectances at some wavelengths as a function of pigment concentration, water content and density of vegetation. Remote sensing either uses simple indexes to determine quantities such as the LAI or use more complex methods such as canopy reflectance models (Fig. 1.16).

Simple indices

One of the most used vegetation indices is the normalized difference vegetation index (NDVI). The NDVI is used for the estimation of vegetation density and in turn for estimating net primary production over varying biome types. It may also be used for monitoring phenological patterns of the vegetative surface, assessing length of phenological cycles (e.g. growing season) and identifying ecoregions.

$$NDVI = (NIR - red) / (NIR + red) \quad (1.5)$$

where NIR is the reflection in the near infrared (0.7 µm -1.1µm) wavelength range, red is the reflection in the red spectral range (0.6 - 0.7 µm). Table 1.3 gives an overview of the sensors installed in the Sentinel-2 satellite and their spectral sampling. The purpose of the chosen wavelengths for spectral measurements are mentioned. Measurements at wavelengths 560, 665 and 865 nm (0.56, 0.665 and 0.865 µm) provide information about chlorophyll content in the vegetation. Measurements at 775 and 842 (0.775 µm and 0.842µm) are performed to determine the LAI.

Table 1.3 Overview of the wavelengths of the reflectivities measured by the Sentinel 2 sensors. Central wavelength, spectral width, spatial resolution as well purpose are shown (Sources Richter et al., 2009; ESA, 2007).

Central wave-length l(nm)	Spectral interval Δl(nm)	Spatial resolu-tion (m)	Purpose
443	20	60	Atmospheric correction (aerosol scat-tering)
490	65	10	Sensitive to browning,vegetation sene-scing, carotenoid, and soil background
560	35	10	Green peak; sensitive to total chloro-phyll
665	30	10	Maximum chlorophyll absorption
705	15	20	Position of red edge, atmospheric correction; fluorescence baseline
740	15	20	Position of red edge, atmospheric correction; retrieval of aerosol load
775	20	20	LAI, edge of NIR plateau
842	115	10	LAI
940	20	60	Water vapour absorption; atmospheric correction
1375	20	60	Detection of thin cirrus for atmo-spheric correction
1610	90	20	Sensitive to lignin, starch and forest aboveground biomass; snow-ice-cloud separation
2190	180	20	Assessment of Mediterranean vegeta-tion conditions; distinction of clay soils for the monitoring of soil ero-sion; distinction between live biomass, dead biomass, and soil.

1.1.4.3. Remote sensing using measurements of the chlorophyll fluorescence

Chlorophyll fluorescence is light re-emitted by chlorophyll molecules during return from excited to non-excited states. It is used as an indicator of photosynthetic activity in higher plants, algae and bacteria. The analysis of chlorophyll fluorescence is an essential tool in plant research with a wide spectra of applications

One of the application is related to stress of plants. During stress plants reduce the photosynthetic activity. The light not used for the photosynthesis has to be reemitted. It is reemitted due to fluorescence at other wavelengths at some defined emission lines. Chlorophyll fluorescence is either measured by applying the measuring device directly on the plant leaf. The device is equipped with a lamp which sends PAR. It measures the reemitted chlorophyll fluorescence at given wavelength bands. Lines often used are situated at 680 to 690 nm and at 750 nm. Spectral measurements can also be done using solar induced fluorescence with remote sensing devices (spectrometer measuring the spectral signal of a plant) (Figure 1.19). Intensity of the line (and of chlorophyll fluorescence) is defined by the ratio of maximum intensity to the mean of the intensities just below and above the line.

To measure chlorophyll fluorescence sensors need a very high sensitivity. This poses still a challenge for satellite remote sensing. Newly released satellites such as SENTINEL are equipped with spectrometers which allow to perform measurements of chlorophyll fluorescence.

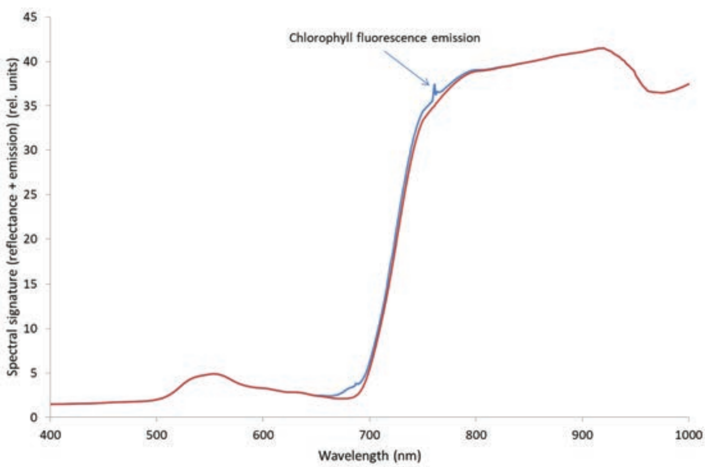


Figure 1.19. Simulated spectral reflectance + emission with and without chlorophyll fluorescence emission (small peaks around 762 nm). Simulations were performed with software Fluormodgui (Zarco-Tejada et al., 2006)

1.2. Agroclimatic indices and models

During the past decades several software tools were developed for agricultural research and decision making purposes. Models can describe system processes using simple to very complex approaches, considering just parts of a complex system (such as soil temperature or soil water balance) or more complex, interacting systems (such as crop growth, considering all relevant interactions of the soil-plant-atmosphere system). They further can limit to physical processes, bio-physical interactions or extend their "system" to human interactions, e.g. linking biophysical with socio-economic models (such as farm models in agriculture and land-use change models at a global scale). In agriculture, crop and whole farm system modeling, pest and disease warning models/algorithms, models for irrigation scheduling and agroclimatic indices or algorithms can significantly help farmers in decision making for crop management options and application of related farm technologies.

For research purposes, models can be used to simulate and analyze the complex interactions in the soil-plant-atmosphere system. For example, they can be applied to analyze climate change impacts on crop water balance and crop yields. Nevertheless, these modeled systems include many uncertainties and limitations resulting from unknown trends in future technology and human activities, a simplified representation of reality, lack of knowledge on system responses or lack of calibration data.

Agroclimatic indices, either crop specific or not, are widely used in operational forecasting to express agroclimatic risks related to specific weather phenomena. Well known examples are frost risk, drought forecast, sowing and harvest conditions. Also in research agroclimatic indices were already used to express conditions under climate change, such as for drought and heat extremes.

For the presentation of the work that can be done with one agroclimatic index model we choose AgriClim. This model was widely used in different assessment studies and it is free of charge for the research purpose.

1.2.1. AgriCLim - Description of the model

AgriClim is a software package for assessment of changes in agroclimatic conditions and calculation of agroclimatic indices. The core of the package was developed and tested between 2005 and 2009 at the Institute of Agrosystems and Bioclimatology (Mendel University of Agriculture and Forestry in Brno) (Fig. 1.20). Since it is developed as part of the COST 734 action, AgriClim's internal database is based on data collected from 19 member states of the action (Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Ireland, Italy, The Netherlands, Norway, Serbia, Slovakia, Sweden, Spain, Switzerland). AgriCLim uses daily inputs of global radiation, maximum and minimum temperatures, precipitation, air water vapour pressure and mean daily wind speed to calculate more than 200 agrometeorological parameters and indices (Trnka et al., 2010a, Trnka et al, 2011). It is particularly suited to analyse the occurrence of agrometeorologically adverse events that are capable to significantly affect the yields but are often not considered by dynamic crop models, so they are neglected in related studies of climate change impact and adaptation. Detailed description of the AgriClim architecture, indices that can be calculated using AgriClim and reasoning behind implementation of particular models and thresholds are given in Trnka et al. (2010a, 2011). The following text is mainly based on these two references.

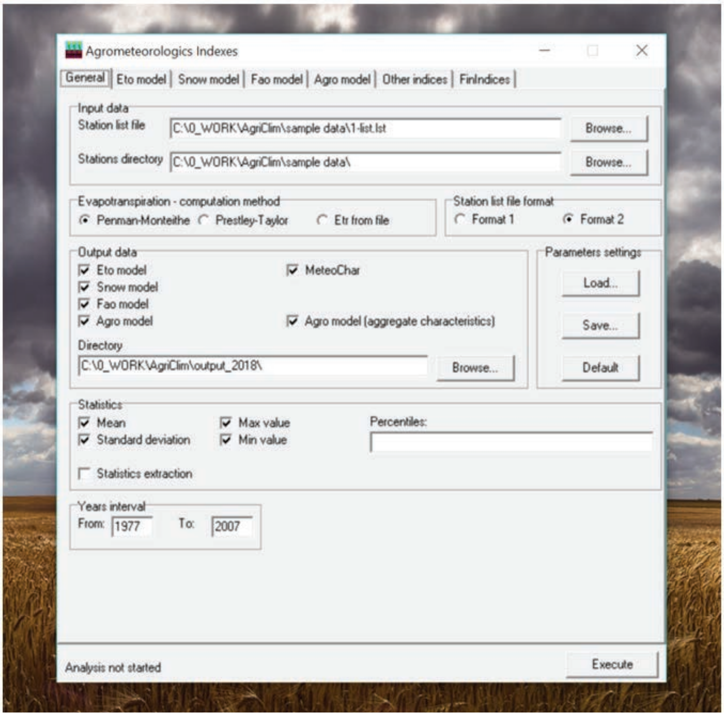


Figure 1.20 AgriClim model.

1.2.1.1. AgriClim Algorithms

Input data for AgriClim are: SRAD - sum of daily global radiation (MJ m^{-2} day^{-1}), TMAX - maximum daily air temperature (°C), TMIN - minimum daily air temperature (°C), RAIN - daily amount of precipitation (mm), VAPO - water vapor pressure (hPa, kPa) or RH (%), units are set on the “Eto model”, WIND - wind speed 10 m above the surface (m s^{-1})

Based on daily inputs, AgriClim use a collection of models:

- Snow cover (presence, duration, start/end date);
- Eto model (calculate potential evapotranspiration);
- Fao model (calculate growth and current evapotranspiration);
- Agro model (calculate basic agrometeorological indices);

Together with other specific indices like FinIndices (calculate indices specific to Finland).

Calculation of snow cover influence is based on a modified version of the model described in Trnka et al. (2010b). Snow was taken into account only at the time of melting, and no evapotranspiration is assumed on days with snow cover present; this is replaced by the constant rate of sublimation on days without precipitation (1.0 mm day^{-1}).

The soil water balance model was calibrated and validated for the range of soil and climate conditions in Central Europe and the

US using an extensive archive of experimental data. Information on soil water content is provided in two predefined layers together with values of daily reference and actual evapotranspiration. When calculating the actual soil water content, homogenous soil conditions and a soil water-holding capacity of 20 mm in the top 0.1 m were assumed in order to estimate the number of sowing and harvest days. The soil profile necessary for calculating some of the indices was based on the clay-loam deep Chernozem soil profile with a maximum rooting depth of 1.3 m and a soil water holding capacity of 270 mm. Although the soil conditions vary across the grid, to allow grid-to-grid comparability, the same soil profile was used at all sites. While calculating the evapotranspiration, an adjustment for the increased CO_2 concentration was always made using the method proposed by Kruijt et al. (2008), and the CO_2 ambient air concentration for the time horizon of the study (i.e. 2050) was set at 536 ppm with the baseline calculations set at 360 ppm.

In version 2018 Fao model can be used for: Spring crop, Winter crop, Fodder plant, Maize, Conifer treess and Deciduious trees.

1.2.1.2. Agrometeorological indices in AgriClim

Agrometeorological indices are numerical indicators that describe various aspects of complex relations between climate and crops. Some of the most important indices that can be calculated using AgriClim, are indicated in the Table 1.4 below.

Table 1.4 Example of agrometeorological indices present in AgriClim

Abreviation	Name	Inputs parameters	Definion	Output format
Heat-Stress_Early	Heat stress days	TMAX	Number of days between January to June 15 with TMAX>28°C	Numbrer of days
SVegS	Begining of growing season	Tmean, Snow	Tmean continuously > 5°C (i.e.does not drop below threshold for more than 3 days) and NO snow	Start date
DVeg-Summer	Duration of vegetation summer	Tmean	Number of days with Tmean continuously > 15°C (i.e.does not drop below threshold for more than 3 days); TMIN above 0°C	Duration
SumEf_10	Sum of effective temperatures above 10°C	Tmean, TMIN, TMAX, Tbase = 0	sum of effective temperatures above 10°C when Tmean was continuously above 10°C and TMIN was never below 0°C	Sum of temperatures per year

Snow-Days	Number of days with snow cover	snow cover	Number of days with snow from September 1 to August 31	Number of days
Frost-Stress_10	number of days with frost below -10°C without snow cover	snow cover, TMIN	Number of days with TMIN<-10°C and no continuous snow cover (i.e. snow cover below 3 cm)	Number of days
FrostRisk-Probability_till summer	Probability of frost risk during growing season	TMIN	Number of seasons when Tmin below or equal to -0.1°C occured during growing season till end of July	% Of seasons
Harvest_June_abb	Number of days suitable for harvest_June	Rain	Number of days per month when A) daily precipitation on day N < 0.5 mm; B) daily sum of preciptitation on day N - 1 is < 5 mm; c) daily sum of precipitation on day N-2 < 10mm and d) daily sum of precipitation on day N-3 < 20mm and e) water content in top 20 cm is between 0-70% of maximum soil water holding capacity	Number of days
Harvest_July	Number of days suitable for harvest_July	Soil moisture in top 20 cm; Rain	Number of days per month when A) daily precipitation on day N < 0.5 mm; B) daily sum of preciptitation on day N - 1 is < 5 mm; c) daily sum of precipitation on day N-2 < 10mm and d) daily sum of precipitation on day N-3 < 20mm and e) water content in top 20 cm is between 0-70% of maximum soil water holding capacity	Number of days
TotalDuration of HeatW3	Sum of days per year fitting to HeatW3 conditions	TMAX, TMIN	Total number of days within episodes when TMAX is continously above 30°C for at least 3 days and TMIN above 20°C	Number of days
Hughlin index	Hughlin index	Tmax, Tmin, Tmean,	Hughlin index for period from April-September	Index value (°c)

WatBal_AMJ	Potential water balance April-June	ET0, RainC	difference between RainC-ET0 (defined period)	Sum (mm)
WatBal_AS	Potential water balance April-September	ET0, RainC	difference between RainC-ET0 (defined period)	Sum (mm)
DryI_AMJ	Number of days with intensive water deficit for April-June	AET, ET0	one value per period/year	Number of days in defined period when AET/ET0 < 0.4
DryI_AS	Number of days with intensive water deficit for April to September	AET, ET0	one value per period/year	Number of days in defined period when AET/ET0 < 0.4
SRAD_LGPt	Effective global radiation sum	Tmean, AET, ET0, SRAD	sum of daily global radiation during days with Tmean > 5°C and AET/PET > 0.4	MJ/m2/day
Vernalization	Number of days suitable for vernalization	Tmean, Tmin	number of days with conditions suitable for vernalization	Days
WinterSeverity	Severity of winter	Tmean	sum of freezing temperatures	°C

1.2.2. Use of AgriClim for Serbian agroecological conditions

One of the main features of the index models are wide spread of the indices that can be used in the analysis. This spread is a result of the real difference in regional agroclimatic conditions.

As mentioned before AgriClim Fao model can be used for Spring crop, Winter crop, Fodder plant, Maize, Conifer trees and Deciduous trees. Deciduous trees are extremely large group of horticultural plants consisted of wide range of angiosperms that populate all floristic regions across the globe. In addition to ample diversity in forms, growth and reaction norms, when species are grafted on different rootstocks those parameters shift. This makes agro meteorological models partly applicable and difficult to explain the obtained results in comparison with in vivo plant indicators. Potential implication in grape and fruit production lies in prediction of pest and disease prediction, rather than yield forecast. In Serbia there are no precise data regarding yields even for the main fruit crops. Annual reports are cumulative and regional. Thus approach for fruit trees should be reverse, first calculate the main agro meteorological indices and then obtain the data regarding yields in the specific years and localities that have shown drought and heat stress indicators.

AgriClim was run with observed meteorological data from meteorological station placed at Rimski Sancevi (45°15N, 19°50E, 84 m a.s.l.). This station is part of the observational network of Hydrometeorological Service of Serbia. Model was run with set of meteorological data: (i) sum of daily global radiation (MJ m^{-2} day^{-1}), (ii) maximum daily air temperature (°C), (iii) minimum daily air temperature (°C), (iv) daily amount of precipitation (mm), (v) water vapor pressure (hPa) and (vi) wind speed 10 m above the surface (m s^{-1}) for winter crops. The results are shown in the form of tables and graphs in order to characterise years with water deficit and to highlight years where cause of yield depletion was drought.

Temperature

Description of vegetation dynamics is made with sums of temperature above certain threshold (0, 5 and 10°C) during the vegetation period or during the year together with number of days with extreme temperature events (Table 1.5).

Table 1.5 Daily temperature extremes del.

	Maximum temperature (°C)	Minimum temperature (°C)
Frost day	–	≤ 0
Freeze day	≤ 0	–
Strong frost day	–	≤ -10
Summer day	≥ 25	–
Tropical day	≥ 30	–
Tropical night	-	≥ 20

Years with larger sums of temperature are extracted from Table 3 and presented on the graph in the form of deviation from average, by subtracting from average (Figure 1.21). Positive values on the Fig. 1.21 are showing years where sums of temperature above 0 were small, negative values are showing on years with large sums of temperature pointing into the possible drought appearance.

Table 1.6 Sum of temperature above 0°C del.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1977	87.3	197.2	308.8	311.9	523.6	593.9	646.5	637.3	453.6	394.6	217.2	34.9
1978	58.3	70.0	246.0	321.6	446.2	553.3	613.5	606.3	471.3	354.6	75.0	102.6
1979	56.6	88.8	298.3	300.4	526.9	642.5	600.2	620.7	538.4	335.2	203.2	158.2
1980	19.7	71.4	194.0	260.7	425.7	579.2	621.6	626.2	489.0	380.8	157.7	41.9
1981	15.3	59.4	293.5	333.9	497.5	597.0	630.5	639.3	546.5	419.7	154.4	73.3
1982	49.3	17.5	178.3	245.9	541.8	614.0	650.5	648.2	618.0	431.2	182.2	140.9
1983	131.3	54.7	261.0	419.3	558.8	567.9	694.2	664.7	519.5	355.6	113.4	90.6
1984	54.1	55.8	168.0	313.1	497.6	534.3	581.4	618.7	552.3	420.0	199.3	60.7
1985	31.8	21.3	167.0	359.0	562.3	523.4	649.1	661.2	516.5	331.7	147.6	184.5
1986	66.1	14.7	156.3	415.2	569.9	565.9	607.2	684.9	515.2	357.4	165.4	43.8
1987	14.3	80.1	108.3	329.4	462.6	597.2	720.5	604.7	615.5	400.0	215.8	104.4
1988	118.4	124.9	173.1	313.8	519.1	582.6	711.8	682.9	523.6	349.9	54.8	98.6
1989	25.3	150.0	300.9	437.1	478.4	541.8	678.4	661.3	514.5	389.4	177.6	127.0
1990	100.3	186.8	309.5	340.1	534.2	582.5	653.0	670.4	469.3	406.5	215.4	52.5
1991	90.3	26.0	265.6	285.9	404.0	591.5	671.3	630.8	537.3	342.8	205.9	14.2
1992	**70.3**	114.7	217.1	369.7	516.0	599.8	669.3	795.7	539.5	368.4	234.7	79.4
1993	82.4	7.8	163.1	343.4	584.1	600.4	653.4	685.2	**517.0**	**430.2**	**108.5**	**122.8**
1994	111.1	104.0	287.4	355.0	517.5	596.8	730.0	723.3	628.7	328.9	218.1	87.9
1995	56.4	196.7	196.4	341.6	496.6	579.9	715.2	650.5	484.5	398.3	122.8	77.6
1996	**28.9**	**14.3**	**96.2**	**347.7**	**563.7**	**610.1**	**610.7**	**648.8**	**408.5**	**377.3**	**275.5**	**78.3**
1997	**2.5**	**119.2**	**176.4**	**229.3**	**542.1**	**611.9**	**631.7**	**640.0**	**495.9**	**281.5**	**210.1**	**118.0**
1998	132.1	172.5	136.4	396.3	494.4	644.9	674.7	676.3	491.4	416.1	140.6	12.1
1999	62.8	78.4	264.3	392.1	521.3	605.4	667.9	665.6	591.7	388.2	143.1	96.5
2000	**21.9**	**130.6**	**223.1**	**442.3**	**573.7**	**639.9**	**777.0**	**747.6**	**534.7**	**466.5**	**346.2**	**131.5**
2001	114.4	134.3	337.2	332.8	552.3	545.3	686.8	703.6	477.2	461.0	126.4	9.1
2002	78.5	204.1	276.1	349.4	593.6	652.6	727.3	685.8	512.2	392.2	300.9	69.9
2003	**39.6**	**0.8**	**184.9**	**327.9**	**637.1**	**717.2**	**698.9**	**760.9**	**517.3**	**323.6**	**248.2**	**88.0**
2004	48.0	93.6	213.1	371.9	470.2	590.4	677.2	675.6	491.3	436.2	208.7	94.6
2005	60.8	15.6	178.9	358.6	521.0	576.7	663.6	622.7	538.1	387.9	165.4	80.5
2006	30.7	73.2	185.4	388.0	507.8	580.9	724.5	627.1	557.8	443.8	244.6	103.5
2007	**206.1**	**181.1**	**286.6**	**386.5**	**573.8**	**663.8**	718.6	713.4	461.6	339.4	136.2	60.2
Ave-rage	66.6	92.2	221.0	345.8	523.0	596.2	669.5	667.1	520.2	384.1	184.3	85.1

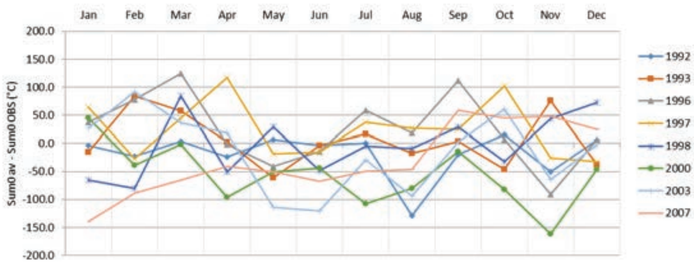


Figure 1.21 Difference between average and observed sums of temperature above 0°C in selected years

Table 1.7 Sum of temperature above 10°C

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1977	0.6	17.9	54.0	55.7	213.6	293.9	336.5	327.3	159.1	88.7	26.1	0.0
1978	0.0	3.9	22.2	52.0	146.6	253.3	303.5	296.3	172.5	76.5	0.0	1.3
1979	2.5	0.0	35.1	38.7	218.2	342.5	290.2	310.7	238.4	72.0	14.7	2.8
1980	0.0	0.0	10.4	27.0	121.8	279.2	311.6	316.2	189.0	84.9	1.6	0.0
1981	0.0	0.0	36.8	64.1	187.6	297.0	320.5	329.3	246.5	124.9	9.8	0.0
1982	0.0	0.0	5.3	20.3	234.4	314.0	340.5	338.2	318.0	123.1	2.6	5.7
1983	1.1	0.0	29.7	139.0	248.8	267.9	384.2	354.7	219.5	75.8	2.4	0.8
1984	0.0	0.0	9.7	35.8	190.1	234.3	271.6	308.7	252.3	118.3	17.1	0.0
1985	0.0	0.0	3.1	74.0	253.4	223.4	339.1	351.2	216.5	81.0	5.7	4.7
1986	0.0	0.0	12.6	141.3	259.9	265.9	297.2	374.9	215.2	60.7	1.6	0.0
1987	0.0	0.0	8.4	59.8	155.4	297.2	410.5	294.7	315.5	114.9	9.6	0.0
1988	0.7	0.9	5.2	50.7	209.1	282.6	401.8	372.9	223.7	78.6	0.0	0.0
1989	0.0	16.4	37.1	141.2	173.6	241.8	368.4	351.3	214.5	86.6	30.7	21.9
1990	0.9	4.6	41.0	57.4	224.2	282.5	343.0	360.4	169.3	123.6	22.5	0.0
1991	0.0	0.0	33.1	24.2	96.3	291.5	361.3	320.8	237.3	111.5	3.9	0.0
1992	0.0	0.0	19.1	92.1	206.2	299.8	359.3	485.7	239.5	85.1	22.6	0.0
1993	0.0	0.0	22.3	78.1	274.1	300.4	343.4	375.2	217.0	141.1	15.3	0.0
1994	2.8	0.8	27.9	78.3	207.5	296.8	420.0	413.3	328.7	63.1	23.0	0.2
1995	1.6	4.2	4.5	94.3	188.3	279.9	405.2	340.5	185.8	108.8	6.9	6.6
1996	0.0	0.0	0.0	82.4	253.7	310.1	300.7	338.8	109.4	92.0	52.7	0.0
1997	0.0	5.5	2.4	27.9	232.4	311.9	321.7	330.0	195.9	63.2	27.1	0.0
1998	0.9	13.9	6.1	102.6	184.4	344.9	364.7	366.3	191.4	116.5	12.4	0.0
1999	0.0	0.0	23.3	92.9	211.3	305.4	357.9	355.6	291.7	102.4	9.7	0.5
2000	0.0	0.0	23.8	156.9	263.7	339.9	467.0	437.6	234.7	164.5	67.7	2.2
2001	1.8	6.3	70.3	57.4	242.3	245.3	376.8	393.6	177.5	164.5	2.3	0.0
2002	0.3	10.9	26.0	75.4	283.6	352.6	417.3	375.8	212.2	87.9	54.9	0.0
2003	0.0	0.0	19.9	71.1	327.1	417.2	388.9	450.9	217.3	72.0	26.3	0.0
2004	0.0	1.5	34.0	83.9	160.3	290.4	367.2	365.6	191.3	136.0	21.7	5.3
2005	0.0	0.0	22.6	74.0	215.3	278.1	353.6	312.7	238.1	97.4	5.5	0.0

2006	0.0	1.1	29.7	101.1	197.8	280.9	414.5	317.1	257.8	148.7	20.6	3.8
2007	**3.0**	**4.3**	**20.9**	**88.7**	**263.8**	**363.8**	**408.6**	**403.4**	**161.6**	**66.6**	**0.1**	**0.0**
Ave-rage	0.5	3.0	22.4	75.4	214.3	296.2	359.6	357.1	220.5	101.0	16.7	1.8

For the selection of the possible late frost impact numbers of freeze and frost days were counted in the 1977-2007 timeseries. Months of interest are March, April and May when plants can be seriously damaged by low air temperatures (Table 1.8). In Table 1.8 fields with more than 15 frost days in March and more than 3 frost days in April are highlighted.

Table 1.8 Number of freeze and frost days

	Freze Tmax ≤ 0°C Jan	Frost Tmin ≤ 0°C	Freze Tmax ≤ 0°C Feb	Frost Tmin ≤ 0°C	Freze Tmax ≤ 0°C Mar	Frost Tmin ≤ 0°C	Freze Tmax ≤ 0°C Apr	Frost Tmin ≤ 0°C	Freze Tmax ≤ 0°C May	Frost Tmin ≤ 0°C
1977	1	16	1	5	0	4	0	2	0	0
1978	6	23	6	16	0	6	0	1	0	1
1979	13	23	0	16	0	6	0	4	0	0
1980	19	28	1	16	0	9	0	1	0	0
1981	13	28	1	20	0	3	0	2	0	0
1982	17	24	5	25	0	8	0	3	0	0
1983	0	12	5	20	0	6	0	0	0	0
1984	2	21	8	20	0	12	0	3	0	0
1985	20	27	16	27	0	5	0	0	0	0
1986	2	21	12	24	1	12	0	1	0	0
1987	15	29	6	16	10	**19**	0	0	0	0
1988	0	16	0	12	0	10	0	4	0	0
1989	6	30	1	12	0	3	0	0	0	0
1990	13	20	0	13	0	4	0	0	0	0
1991	6	21	8	24	0	5	0	1	0	0
1992	7	20	1	15	0	**15**	0	3	0	0
1993	9	25	7	27	3	14	0	2	0	0
1994	2	15	7	16	0	3	0	0	0	0
1995	13	24	0	7	0	9	0	4	0	0
1996	7	24	11	28	1	**20**	0	1	0	0
1997	10	30	2	16	0	**20**	0	**8**	0	0
1998	5	10	1	16	0	**20**	0	0	0	0
1999	8	23	4	20	0	8	0	0	0	0
2000	14	27	0	17	0	14	0	1	0	0
2001	0	17	0	16	0	1	0	2	0	0

2002	11	22	0	7	0	9	0	1	0	0
2003	12	26	20	28	0	17	0	**6**	0	0
2004	12	21	2	16	0	10	0	0	0	0
2005	6	24	6	25	4	17	0	1	0	0
2006	8	25	5	17	1	14	0	0	0	0
2007	0	6	0	10	0	1	0	0	0	0

The average date of the onset of last spring (late) and first autumn (early) frost for the period 1977-2007 (Table 1.9) have shown that area around Rimski Sancevi is exposed to late and early frosts. The larger standard deviation in the late frost is showing its frequency of appearing later in the year in the last week of the April when many plants are in the critical developing stage.

Table 1.9 The average date of the onset of last spring (late) and first autumn (early) frost

1977-2007	Late frost		Early frost	
Mean	96	06.04.	302	29.10.
StdDiv	16	16.01.	10	10.01.
Max	133	13.05.	325	21.11.
Min	64	05.03.	283	10.10.

Precipitation

At different stages of development, plants have different moisture requirements, as well as the ability to deal with a lack of moisture in the soil. If other environmental factors are at optimal level (temperature, radiation, soil nutrition) the development and finally yield will predominantly depend on the amount of available water. In the climate assessment studies sums of precipitation is mostly given annually. Since we are focusing on the plant, sums are given year by year monthly in order to investigate impact on plant development (Table 1.10).

Table 1.10 Sums of precipitation in mm

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1977	37.6	94.4	54.6	58.8	52.3	84.3	49.2	107	34.6	16	90.7	59.1
1978	30.9	85.7	40.1	35.7	126.2	128.4	26	11.7	71.1	2.7	9.6	42.7
1979	60.6	33.5	33.4	25.7	23.6	89.9	66.6	69.9	20.4	53.7	43	46.1
1980	32.4	35.3	45.6	53.7	65.4	87.8	41.6	58.1	26.3	42.9	74.5	40.5
1981	35.8	18.4	117.1	39.6	38	204.5	20.4	63.2	85.9	63.7	42.3	99.3
1982	26.3	16.3	56.3	68	22.7	69.7	59	58.9	9.5	48.6	25.8	62.7
1983	43.4	19.7	23.4	31.9	35.9	87.6	58.1	33.7	75.3	27.6	18.7	23.3
1984	66.5	25.3	13.1	40.1	107.7	47.4	98.1	42.4	34.7	56.2	35.3	16.7
1985	30.2	63.7	65	42.6	93.2	77.8	31.4	80	10	11.3	70.3	17.6

1986	52	42.5	37.5	56.9	50.8	50.4	77.1	40	4.3	42	6.7	16.1
1987	101.8	2.3	63.1	80.8	175.7	62	31.6	50.5	5.5	11.9	83.2	29.7
1988	36.2	42.7	95.2	56.8	25.9	64.6	20.1	17.1	55.3	12.1	20	25.2
1989	6.5	8.6	35.2	82.1	66.2	92.5	11.1	72.4	30	32.5	50	19.9
1990	6.3	35.4	33.3	34.2	17.9	69.8	28.4	14.7	54.1	52.8	38.8	67.1
1991	15.1	23.1	46.9	46.6	76.5	71.5	192.9	64.3	35.7	110.7	75.4	20.7
1992	7.1	22.2	3.3	30.9	39	88.1	21.6	0.2	32.1	142.5	84.9	43.9
1993	15.3	5.3	52.9	30.1	39.4	63.6	42.8	35.7	38.2	19.6	68.2	87.4
1994	42	33.6	33	53.5	73.7	101.4	32.2	44.7	42.6	58.5	25.4	33.5
1995	75.1	51.3	42.8	54	86	108.8	40.5	75.9	101.4	0.6	39.6	64.2
1996	46.3	34.5	29.8	25.2	90	79.1	83.8	112.8	119.2	33.1	94.5	65.8
1997	44.1	46.6	32.2	75.2	17.4	62.4	130.5	124.6	30.3	92.2	38.3	81.7
1998	68.1	0.9	22.6	39.8	64.1	103.7	123.5	82.1	76.9	79	66.1	27.9
1999	42.2	47.8	11.1	61.2	77.2	91	209.4	28.2	76.9	52.4	103.8	138.5
2000	15.7	8.1	31.7	24.6	40.4	31.5	29.7	6.4	15.5	6.9	23.4	52.7
2001	38.4	28.6	75.9	156	78.6	237.4	80.4	29.5	160.1	14.7	71.4	27.6
2002	7.5	28.4	10.1	33.4	84.7	27.5	35	53.8	47.5	91.7	23.7	41.6
2003	49.2	21.5	8.9	9.2	21.9	30.7	61.5	30.4	83.3	142.3	29	21.3
2004	53.4	43.3	17.8	118.6	87.9	97.4	65.1	39.3	50.1	86.1	142.9	33.8
2005	30.2	41.6	40.1	33	38.1	135.8	122.5	133.9	67	7.1	19.6	66.5
2006	30.5	43.5	72.5	66	70.1	104.3	30.9	124.9	23.8	17.6	17.2	39.8
2007	47.7	50.7	**78.8**	**0**	**99.4**	71.1	38.8	79.6	78.8	101.4	119.5	32.8
Average	38.5	34.0	42.7	50.5	64.1	87.8	63.2	57.6	51.5	49.4	53.3	46.6

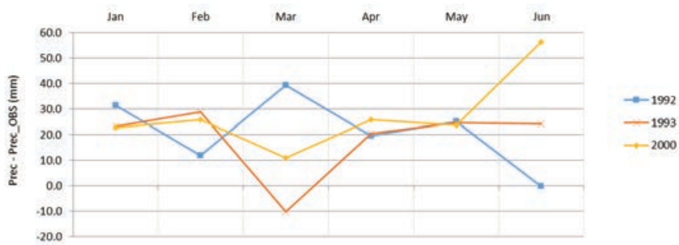


Figure 1.22 Difference between average and observed sums of precipitation in selected years.

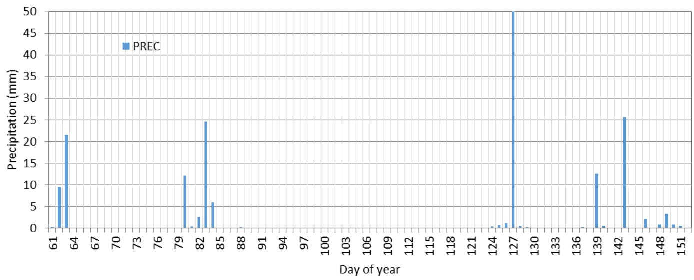


Figure 1.23 Precipitation in March-April-May in 2007.

Evapotranspiration

Evapotranspiration is complex physiological and physiological process in which plant loses water due to evaporation of water from the surface of plants, soil as well as the physiological process of transpiration. Inside the AgriClim evapotranspiration is included according to the definition of the Food and Agriculture Organization (FAO) under reference evapotranspiration is implied the maximum amount of water that plant could lose at given time if the soil is saturated with moisture to the maximal water capacity and evenly covered with grass of 0.12 m height. If these conditions are met real evapotranspiration is equal to reference, in other cases factor that decrees potential evapotranspiration to real need to be used. In agrometeorological practice the intensity of the drought, in addition to other parameters, is expresses through the relation of the real (ET) and reference (ET0) evapotranspiration (ET/ET0). If this relationship is smaller the intensity of the drought is higher. The criteria for drought intensity are formed through the following limit values of the ET/ET0 relationship:

Table 1.11 Number of days with start, intensive, extreme, very extreme and complete drought for periods April-May-June, June-July-August, September-October-November, March-April-May.

Year	Dry (start)				Dry (intensive)				Dry (extreme)				Dry (very ex.)				Dry (complete)			
	AMJ	JJA	SON	MAM	AMJ	JJA	SON	MAM	AMJ	JJA	SON	MAM	AMJ	JJA	SON	MAM	AMJ	JJA	SON	MAM
1977	62	57	73	49	42	40	51	22	28	23	34	6	9	9	1	0	0	0	0	0
1978	5	54	89	0	0	45	86	0	0	39	61	0	0	30	1	0	0	16	0	0
1979	84	60	91	90	55	47	65	32	26	36	42	8	19	16	13	3	0	0	0	0
1980	29	70	88	30	3	56	55	0	0	42	41	0	0	14	11	0	0	0	0	0
1981	14	63	32	12	10	54	11	4	4	30	0	0	0	12	0	0	0	0	0	0
1982	19	61	91	3	11	39	79	0	5	18	40	0	0	1	18	0	0	0	3	0
1983	69	64	78	63	36	44	78	18	29	31	40	12	15	16	9	2	0	0	0	0
1984	62	63	90	50	14	35	60	0	2	11	24	0	0	0	0	0	0	0	0	0
1985	4	59	83	0	0	51	63	0	0	38	51	0	0	17	33	0	0	0	7	0
1986	42	68	91	25	15	48	90	7	5	32	82	2	0	13	36	0	0	0	20	0
1987	2	55	84	1	0	48	82	0	0	24	80	0	0	8	64	0	0	0	15	0
1988	35	83	82	14	15	73	76	4	3	64	74	0	0	46	23	0	0	20	0	0
1989	32	67	80	57	23	61	50	28	3	51	33	3	0	22	8	0	0	0	0	0
1990	76	92	89	73	50	83	55	42	39	73	50	24	7	50	31	3	0	16	0	0
1991	16	35	62	28	8	13	38	1	1	1	17	0	0	0	0	0	0	0	0	0
1992	**73**	**81**	**62**	**85**	**36**	**73**	**52**	**25**	**11**	**47**	**49**	**7**	**0**	**38**	**41**	**0**	**0**	**27**	**6**	**0**
1993	46	88	91	20	23	81	61	4	7	62	36	0	2	36	3	0	0	6	0	0
1994	**31**	**82**	**89**	**11**	**11**	**65**	**62**	**1**	**1**	**41**	**31**	**0**	**0**	**26**	**4**	**0**	**0**	**13**	**0**	**0**
1995	3	51	65	2	0	29	38	0	0	9	24	0	0	0	0	0	0	0	0	0
1996	38	39	51	26	15	29	17	0	4	6	0	0	0	0	0	0	0	0	0	0
1997	36	40	67	11	27	22	26	9	12	12	10	0	0	0	2	0	0	0	0	0
1998	25	43	26	10	10	31	8	0	1	8	0	0	0	0	0	0	0	0	0	0
1999	13	36	59	0	7	23	36	0	1	3	10	0	0	0	0	0	0	0	0	0
2000	**62**	**92**	**91**	**35**	**43**	**91**	**91**	**14**	**26**	**88**	**91**	**0**	**15**	**62**	**69**	**0**	**0**	**33**	**16**	**0**
2001	2	37	50	11	1	19	39	0	0	3	5	0	0	0	0	0	0	0	0	0
2002	56	71	56	40	32	63	39	19	21	52	33	9	5	20	15	0	0	0	0	0
2003	**91**	**91**	**48**	**67**	**83**	**80**	**31**	**53**	**54**	**61**	**16**	**24**	**33**	**38**	**3**	**9**	**1**	**1**	**0**	**0**
2004	2	52	52	0	1	40	32	0	0	26	25	0	0	14	0	0	0	3	0	0
2005	19	21	70	8	12	16	50	2	2	4	0	0	0	0	0	0	0	0	0	0
2006	4	48	78	2	0	38	66	0	0	25	35	0	0	8	4	0	0	0	0	0
2007	47	69	36	28	30	53	25	17	12	24	10	10	1	11	0	1	0	0	0	0
Max	91	92	91	90	83	91	91	53	54	88	91	24	33	62	69	9	1	33	20	0
Average	35	61	71	27	20	48	52	10	10	32	34	3	3	16	13	1	0	4	2	0

- ET/ET0 < 0.5 – start
- ET/ET0 < 0.4 – intensive
- ET/ET0 < 0.3 – extreme
- ET/ET0 < 0.2 – very extreme
- ET/ET0 < 0.1 – complete.

Summing up the data presented above (Table 1.11) several conclusions can be made:

- years with high spring temperature sums (March T10°C > 40°C, average=22.4°C): 1977, 1990, **2001**;
- years with high spring temperature sums (April T10°C > 100, average=75.4°C): 1983, 1986, 1989, 1998, **2000**, 2006;
- years with high summer temperature sums (June T10°C > 350, average=296.2°C): **2003**, 2007;
- years with high summer temperature sums (July T10°C > 410, average=359.6°C): 1987, **1994**, **2000, 2002,** 2006;
- years with low spring precipitation sums (March P < 15mm, average=42.7mm): 1984, **1992**, 1999, **2002**, **2003**;
- years with low spring precipitation sums (April P < 35mm, average=50.5mm): 1983, **1992**, 1993, **2000, 2002, 2003**, 2005, 2007 (0mm);

Years with extreme temperature sums and lack of precipitation have indicated presents of dry conditions which are confirmed with the data given in table 8. The impact of the drought on the agricultural production has been observed in the field in the same periods as indicated 1992-1994 and 2000-2003 for the rainfed crops.

1.2.3. Agrometeorological network

Some parts of the Earth's surface absorb the radiation more efficiently than others resulting with hot spots and zones. The air above is therefore getting warmer that than the air above surrounding colder terrain. The warm "bubble" of air rises, as it rises and expands it cools down. If the "bubble" of air cools down to the dew point temperature condensation of moisture occurs and cumulus cloud is formed. Depending on the temperature gradient and amount of water vapour that warm air is carrying convective cumulonimbus clouds can be formed. The convective rainfall coming from convective clouds are therefore highly dependant of the surface characteristic and their spatial distribution can bring different amounts of water to very close locations.

In the crop modelling this spatial difference in the precipitation amount can bring large errors into calculation. The initial point for the crop modelling is model calibration to real conditions. What are real conditions since in most cases meteorological station form which we collect data is close, but not placed in the field. To investigate how big can be error in the crop model calculation we used AgriClim to compare temperature sums and precipitation amount from the station of Hydrometeorological Service of Serbia placed in Rimski Sancevi (45°15N, 19°50E, 84 m a.s.l.) and data observed on the agrometeorological stations around this location which are a part of the agrometeorological network of Prognostic and Reporting Services for Plant Protection of Serbia (PIS).

Table 1.12 Stations details

Latitude	Longitude	Altitude	Site		
45.39805	19.8201	78	Čenej	CE1216	PIS
45.24902	19.7239	80	Futog	FU1216	PIS
45.38614	19.7745	77	Kisač	KI1216	PIS
45.333	19.85	84	Rimski Šančevi	RS1216	RHMZ

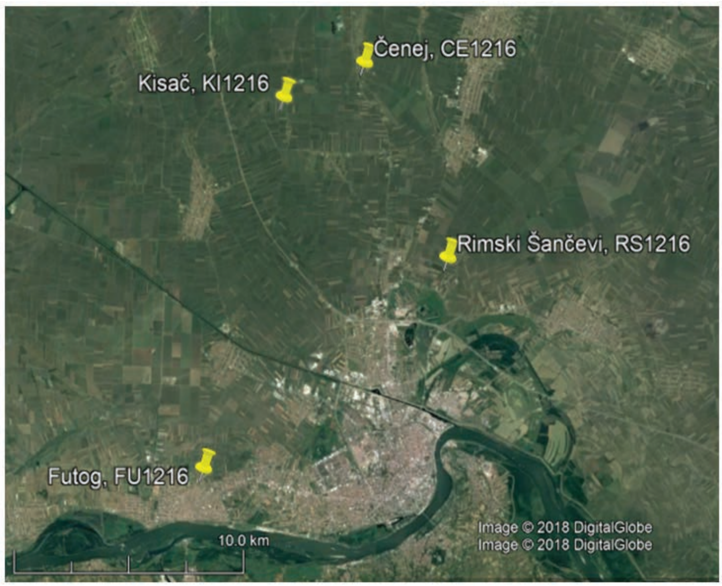


Figure 1.24 Distance between selected stations

For the selected locations (Table 1.12, Figure 1.24) using AgriClim comparison of the average temperatures, sum of temperatures above 10 and sum of precipitation for period 2012-2016 is made (Table 1.13).

Year	RS1216	FU1216	CE1216	KI1216
		Average temperature (°C)		
2012	17.64	17.25	18.18	17.43
2013	17.04	16.60	17.23	17.00
2014	16.60	16.41	17.01	16.64
2015	16.75	16.67	17.28	16.73
2016	17.64	17.42	17.87	17.34
		Sum of temperature above 10°C		
2012	**714.95**	687.60	**769.05**	701.50
2013	669.45	635.30	690.70	670.55
2014	**608.6**	593.85	**646.20**	611.10
2015	644.85	644.00	690.65	641.80
2016	703.15	682.90	725.05	675.70
		Sum of precipitation		
2012	162.5	143.2	195.4	119.4
2013	**279.6**	267.8	**337.6**	271.4
2014	**291.5**	274.4	**361.6**	274.6
2015	234.3	228.2	180.2	173.4
2016	**302.7**	291.8	**267**	239.8

Table 1.13 Average temperature, sum of temperature and precipitation for period April-June.

Results are showing large differences between sum of temperatures and precipitation on all locations, on such small spatial scale. Therefore we need to be very careful when we use station data for the representation of real field conditions.

1.3. Agrometeorological measurements

Agrometeorology is an interdisciplinary holistic science which ties together physical and biological sciences. Although a recent scientific discipline, agrometeorology has faced serious challenges at the beginning of the new millennium. Climate changes and millions of people suffering from hunger are civilizational problems that scientists will have to tackle in the coming years and decades, with agrometeorologists undoubtedly taking an active part in these efforts. The fact that agrometeorology is both interdisciplinary and holistic is simultaneously an advantage and a disadvantage in agrometeorological research. Namely, without a complete understanding of the interactions within the atmosphere-soil-plant system, agricultural technology is unable to answer the questions it faces today. Therefore, the scope of basic agrometeorological data is wide, including not only meteorological but also hydrological, pedological and biological factors that affect plant-environment interactions and hence the agricultural production.

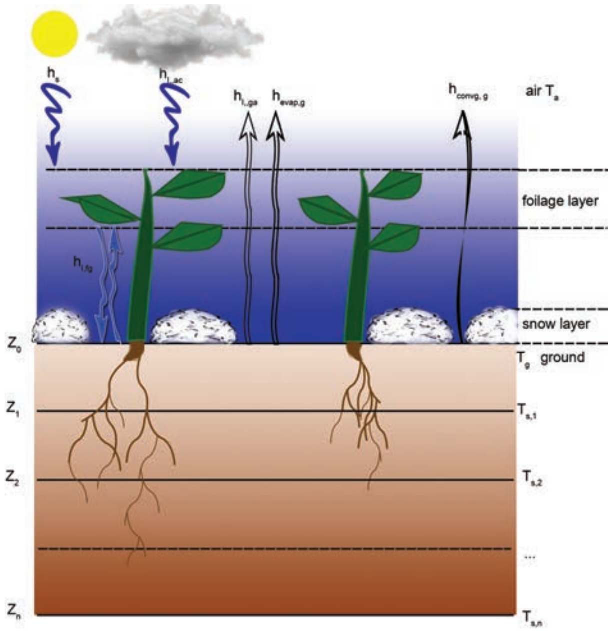


Figure 1.25 Schematic representation of plant cover model.

The space in which measurements and observations are performed for the needs of agrometeorological analysis and forecasts starts from the deepest roots of plants and trees, extending through the air layer above soil surface in which plants and animals grow and develop, and ending in high layers of the atmosphere in which processes such as transport and dispersion of dust, seeds and pollen take place (Figure 1.25). Agrometeorological measurements are expected to meet the needs of plant and animal production, forestry, fishery, indoor and outdoor crop production, agricultural production planning, and transport and storage of agricultural produce.

In addition to the meteorological events and phenomena on large and meso scale (Figure 1.26) which are typically in the focus of interest of the general public, operational agrometeorology also deals with processes and small-scale events which are associated with windbreaks, irrigation, mulching, shading, and frost and hail protection.

Besides meteorological elements, agrometeorological measurements include also hydrological, pedological and biological factors which affect plant-environment interactions and hence agricultural production itself. The range within which measurements and observations are performed for the needs of agrometeorological analyzes and forecasts starts from the deepest roots of plants and trees,

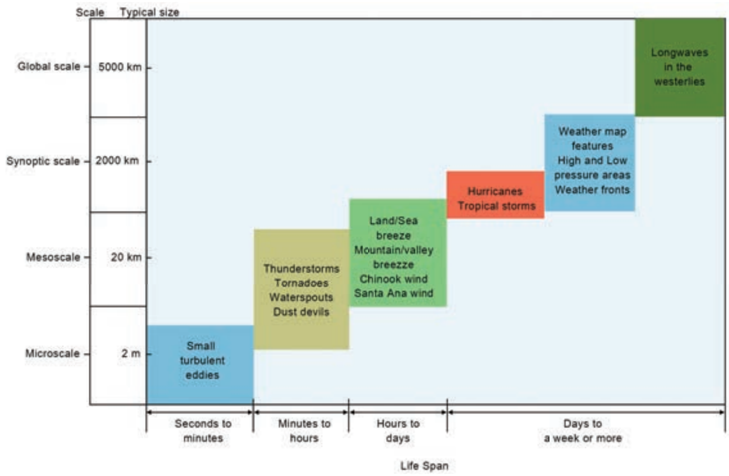


Figure 1.26 Schematic representation of spatial and temporal dimensions of atmospheric circulations

extends over the air layer near soil surface in which plants and animals grow and develop, and ends in high atmospheric layers in which processes such as transport and dispersion of dust, seeds and pollen take place. Agrometeorological measurements are expected to cover the requirements of plant and animal production, forestry, fisheries, indoor and outdoor crop production, agricultural production planning, transport and storage of agricultural products. A particularly important segment of agrometeorological measurements are the measurements for the forecast and monitoring of the occurrence of harmful organisms.

Measurements and observations of physical/meteorological and biological data are essential for providing relevant information to various users: from farmers (both large and small), specialists in plant protection forecast and reporting services, consultants in agricultural advisory (extension) services, researchers in scientific institutions, to experts in charge of designing and proposing strategic measures and plans for the development of agriculture and agriculture-related activities. The way in which these measurements and observations are carried out depends on the purpose for which data are collected. If the purpose is agro-climatic characterization, climate monitoring or natural resource management, long-term regional or country-wide data are required (at least 30-year data in the case of a climatological survey). In the case of: short term decision making early warnings of natural hazards, plant diseases and pests, advisory services for field and crop management, microclimate management and research purposes, additional detailed measurements and observations should be made especially when it comes to biological parameters.

To be able to continually monitor the quality of the provided data, it is important for the measured biological data to be compatible with the meteorological data regarding the spatial and temporal scales on which they have been measured. Biological observations are focused either on possible links between the physical (primarily meteorological) environmental conditions on one side and the dynamics of development of plants and animals on the other (phenological observations) or on impact of these conditions on biomass changes (Manual on the Global Observing System, WMO - No. 544; WMO Technical Notes1). Finally, biological observations that include the assessment of damage caused by extreme weather or harmful organisms, and measurements of growth and yield also should be included.

The scale of agrometeorological measurements ranges from micro to macro scale. According to a World Meteorological Organization document (WMO, 2008b), for the agrometeorological applications, macro scale is greater than 100 km, meso scale ranges from 100 km to 3 km, topo (local) scale ranges from 3 km to 100 m and micro scale is smaller than 100 m.

When we deal with macro-scale phenomena (changes in pressure field as a result of front passage, for example), we can use data measured and registered within the network of synoptic stations of national hydrometeorological institutes. Agrometeorological analyses and forecasts have a specific feature – they often require the use of data in real time. For the planning and activities in the agricultural sector, it is necessary to have data that have been collected on a smaller spatial scale. In some cases, such data can be provided by the appropriate interpolation of the data measured by synoptic meteorological stations (Wieringa, 1998; WMO, 2001b). However, biometeorological research often requires observations at the farm, i.e. microscale.

Without metadata measurements are unreliable. Meteorological measurements do not provide reliable information about the state of the atmosphere on a local scale, unless it is known how the data were measured, including information on the measuring instrument, its position and orientation, frequency of measurements, averaging time, and the method of processing the raw data. When all these elements of the measurement procedure are specified, they are referred to as metadata and their availability determines the value, or quality, of measurement. For example, average wind speed measured at the height of 2 m above ground will be two thirds of the speed measured at the height of 10 m. Also, a maximum air temperature observed with a fast thermometer above dry sandy soil can be several degrees higher than the maximum air temperature measured on the same day, in the same location, but above wet clay soil and using a thermometer with a high coefficient of inertia. When it comes to measurements at synoptic stations within the network of national hydrometeorological services, metadata are under the authority of WMO, which specifies the measurement procedure.

However, the large open space required by the WMO procedures is not always available, and the available budget does not leave much room for solving this type of problem. For agrometeorological stations, which perform different measurements in varying terrain, metadata have always been important, but were usually referred to as „station history". For this reason, it is important that data related to the instruments (type, calibration, maintenance), their position (height, orientation, surroundings at toposcale) and observation procedures are recorded at agrometeorological stations (measurement methods and frequencies, averaging, recording, archiving). More details on metadata in agrometeorological measurements can be found in „WMO_No134_en_Guide to Agricultural Meteorological Practices" (Chapter 2.2.5).

1.4. Weather forecasting

Weather forecasting represents the prediction of weather through the application of the principles of physics, supported by various statistical and empirical techniques. It also includes predictions of changes in the Earth's surface caused by atmospheric conditions (e.g., snow and ice cover, storm surges, and floods).

Forecasts are made using numerical weather prediction (NWP) models. NWP is a method of weather forecasting that employs a set of equations that describe the flow of fluids. These equations, numerical methods, and parameterizations of physical processes are translated into computer codes in order to produce NWP. These features are combined with initial and boundary conditions before being run over a domain (i.e., a geographic area).

To date, many different models have been developed. The complexity of these models has increased in step with computing power over time. One of the first attempts to predict weather was made by Lewis Fry Richardson in 1922. Using a variety of primitive equations, it took him six weeks to forecast the state of the atmosphere over two points in central Europe. Current models are run on supercomputers.

However, computers are not enough. Weather forecasts require 24-hour observations of atmospheric conditions made at weather stations spread around the world. In addition, data from a vast variety of other sources, including satellites, Doppler radar, weather balloons, aircraft, and ships, are also assimilated. This complex system of observations and computing resources today allows predictions on different temporal and spatial scales, as given in table 1.14.

Table 1.14 Definitions of meteorological forecasting ranges (Source: http://www.wmo.int)

1	Nowcasts	Descriptions of current weather parameters and descriptions of forecast weather parameters over the next 0-2-hours.
2	Very short-range weather forecasts	Descriptions of weather parameters over up to 12 hours into the future.
3	Short-range weather forecasts	Descriptions of weather parameters beyond 12 hours and up to 72 hours into the future.
4	Medium-range weather forecasts	Descriptions of weather parameters beyond 72 hours and up to 240 hours into the future.
5	Extended-range weather forecasts	Descriptions of weather parameters beyond 10 days and up to 30 days into the future. Typically averaged and expressed as departures from the climatological values for that period.
6	Long-range forecasts	From 30 days up to two years into the future.
6.1	Monthly outlooks	Descriptions of average weather parameters. Expressed as departures (deviations, variations, or anomalies) from the climatological values for that month (not necessarily the coming month).
6.2	Three-month or 90 day outlooks	Descriptions of the average values of weather parameters. Expressed as departures from the climatological values for that 90-day period (not necessarily the coming 90-day period).
6.3	Seasonal outlooks	Descriptions of the average values of weather parameters. Expressed as departures from the climatological values for that season.
7	Climate forecasts	Beyond two years.
7.1	Climate variability predictions	Descriptions of the expected values of climate parameters associated with the variations in inter-annual, decadal and multi-decadal climate anomalies.
7.2	Climate predictions	Descriptions of expected future climate conditions, including the effects of both natural and human driving factors.

Notes:

- In s*ome countries, long-range forecasts are considered to be climate products*
- *Seasons are loosely defined as Dec/Jan/Feb = winter; Mar/Apr/May = spring; etc., in the Northern Hemisphere. In tropical areas, the seasons may have different durations. Outlooks spanning several months, such as multi-seasonal outlooks or tropical rainy season outlooks, may be provide*d.

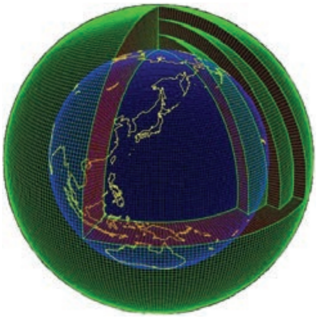


Figure 1.27 Global horizontal and vertical grid (https://public.wmo.int/en/our-mandate/weather)

Almost all physiological and biochemical processes that have importance in the development of plants and harmful organisms are triggered and/or limited by temperature (lower and upper thresholds), and the rates of these processes are often proportional to the amount of available energy. Therefore, if numerical models describing specific environmental processes that are dependent on weather are known, numerical weather prediction can be used in model runs and to produce predictions of future changes. In the case of agriculture, the application of monthly and seasonal weather forecasts is of particular importance. The best effects of this practice can be achieved through the use of long-term weather forecasts as input data in well-calibrated and validated forecasting tools, such as physiological, phenological, agrometeorological, crop yield and pest and disease models.

Physiological and biochemical processes occur on specific scales and are best represented using varying time steps. The physiological processes of plants require more time than, for example, disease/pest development, but these processes are spatially limited. Process-specific data then determine which type of weather forecast can be used. In practice, in forecasts of the appearances of disease or pests, the accuracy of predictions is very important, and short-range forecasts are primarily used. In other applications, such as estimating the extent of a certain phenological phase of a crop species, forecasts with longer lead times can be used. A key question in all applications of numerical weather prediction is, 'How far in advance can weather forecasting be used without a significant reduction in the accuracy with which this process can be predicted?' The answer to this question is highly dependent on the process itself.

In the following text, different applications of forecasting are presented.

1.4.1. An application of short-range weather forecasting

1.4.1.1. Short-range weather forecasting

The WorkEta model is a descendant of the Hydrometeorological Institute and Belgrade University (HIBU) model, which was developed in the 1970s in the former Yugoslavia; the earliest relevant reference is Mesinger and Janjic (1974). In the 1980s, the code was upgraded to use the Arakawa-style horizontal advection scheme of Janjic (1984); an advanced physical package was subsequently added (Janjic, 1990) at the National Centers for Environmental Prediction (NCEP; Washington, USA).

1.4.1.2. Application to agrometeorology and crop modelling

The latest version of the WorkEta NWP model is used to obtain forecasts of meteorological parameters up to 4 days in advance. The outputs from the forecast are used to run the biometeorological system for messages on the occurrence of diseases in fruits and vines (BAHUS) (Mihailovic et al. 2001). Part of the BAHUS model that estimates the appearance of apple scab was used at two locations, Rimski Sancevi in Serbia and Goettlesbrunn in Austria (Lalic et al., 2016). From the meteorological outputs, accumulated degree days with base values of 5 and 0 °C are calculated to compare observations with modelled temperature sums for a one-day forecast (D1), a two-day forecast (D2), a three-day forecast (D3), a four-day forecast (D4) and the observed meteorological data (O) during March 2011 (DOY, day of the year) (Figure 1.28).

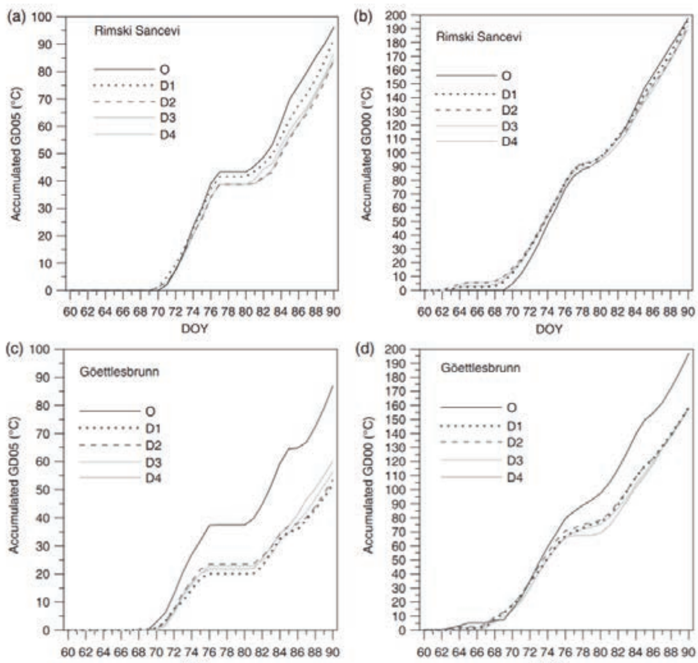


Figure 1.28 Comparison of accumulated growing degree days calculated using a one day forecast (D1), a two-day forecast (D2), a three-day forecast (D3), a four-day forecast (D4) and observations (O) during March 2011 (DOY, day of the year) (Lalic et al., 2016).

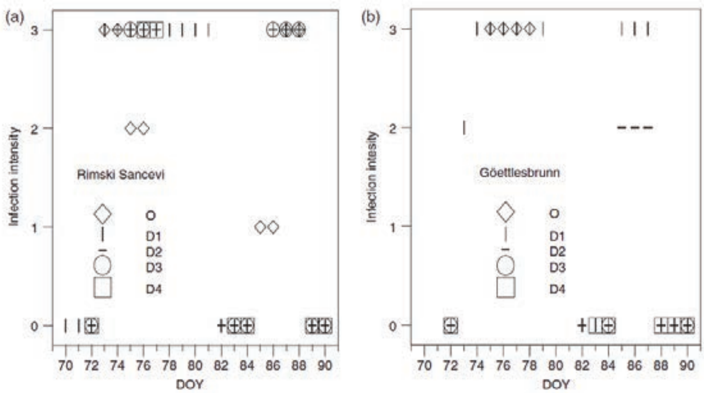


Figure 1.29 Apple scab infection intensity calculated using a 1-day forecast (D1), a 2-day forecast (D2), a 3-day forecast (D3), a 4-day forecast (D4) and observed meteorological data (O) during March 2011 for two locations (Lalic et al., 2016).

The results indicate that weather forecasts, including 4-day forecasts, display promise in predicting accumulated GDDs but show less skill in predicting the meteorological conditions that are relevant for the initiation of the incubation period (Figure 1.28 and 1.29).

Following this example, another numerical weather prediction model is used to test the efficacy of numerical weather prediction use for the prediction of downy mildew appearance on wine grapes. For this experiment, the WRF model is used. WRF represents a state-of-the-art atmospheric modelling system that is designed for both meteorological research and numerical weather prediction. The forecast is performed 4 days in advance, and meteorological values are used to run BAHUS for two locations in Serbia (Cerevic and Vrsac). The values of the meteorological variables differ slightly between the two locations, but the start of the primary incubation is accurately predicted. This finding again confirms that short-range weather forecasts are a powerful tool in disease appearance prediction and can be used operationally (Firanj Sremac et. al., 2016).

1.4.2. An application of extended-range weather forecasting

1.4.2.1. Extended-range weather forecasting

The extended-range forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF) provide an overview of conditions over the coming 46 days and focus mainly on week-to-week changes in the weather (https://www.ecmwf.int). To produce the ensembles (ENS) of extended product (monthly forecasts), coupled ocean-atmosphere integrations are used. The ocean model is introduced since ocean variability with the time step of 10 to 30 days has an impact on atmospheric circulation. Ensembles are created by running the model multiple times with slight changes to original input data. The reason for this is that weather forecasting models take a huge amount of data into them, and within this data there will always be some errors and inaccuracies, so by making changes to that data you can understand how those inaccuracies may affect the forecast. A control is also run, which is the data without any changes to it. Ensembles are introduced because the model cannot accurately predict the exact values of meteorological parameters; however, the probability of occurrence of different values can be determined using ensembles.

To estimate the effects of possible initial errors and the consequent uncertainty of the forecasts, small changes to the 4D-Var analysis are made. This process results in an ensemble of many (currently 50) different, "perturbed", initial states. Model deficiencies are represented by a stochastic process. If forecasts starting from these perturbed analyses more or less agree with the forecast from the unperturbed analysis (the control forecast of the ensemble), then the atmosphere can be considered to be in a predictable state, and any unknown analysis errors will not have a significant impact. In such cases, it is possible to issue a categorical forecast with great certainty. On the other hand, if the perturbed forecasts (the ENS) deviate significantly from the control forecast and from each other, the atmosphere can be concluded to occupy a rather unpredictable state.

The source of predictability in monthly forecasts covering Europe is believed to be the Madden-Julian Oscillation (MJO), which is a 40-50-day tropical oscillation (Ferranti et al., 1990; https://www.ecmwf.int).

1.4.2.2. Practical use of ensemble forecasts

A verification methodology that includes the calculation of the root mean squared error (RMSE) and the ensemble spread (SPRD) can be used to evaluate the ensemble-based values. Because each ensemble member (EM) has equal probability, the RMSE, which represents a measure of the forecast accuracy of crop model outputs (CMOs), is calculated for each year to compare the values of the CMOs calculated using the EMs and the observed data, as follows:

$$RMSE = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\sum_{j=1}^{n}\left(A_{ji} - A_i^{OB}\right)^2} \tag{1.6}$$

where A_{ji} is the value of variable A for the ith element of the sample (day in this case) and the j^{th} ensemble member; A^{OB} is the observed value of A on the i^{th} day; m is the sample size (182 days); and n is the ensemble size. Commonly, the ensemble average (1/n ΣA_j)i of variable A for the i^{th} element of the sample is denoted $A^{EA}{}_i$. The SPRD, which represents the uncertainty of the ensemble, is defined as follows:

$$SPRD = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\frac{1}{n-1}\sum_{j=1}^{n}\left(A_{ji} - A_j\right)^2} \quad (1.7)$$

1.4.2.3. Application to agrometeorology and crop modelling

The monthly forecasts (MWF) produced by ECMWF can be used to predict crop dynamics, soil moisture deficits, evapotranspiration, LAI development, yield and biomass formation. Weather data are used to run models that are able to numerically determine these parameters.

To examine the possibility of using monthly forecasts to assess agroecological conditions in Serbia and Austria, forecast and observed extreme temperatures are compared over a 4 months. Quantification of the forecasts efficiency was determined by root mean square error and spread of the ensemble forecast. Results are given in Table 1.15.

Table 1.15 RMSE and SPREAD for monthly average maximum and minimum temperatures from March 1, 2005 till June 30, 2005 obtained using 50 ensemble members (Table denotation: M-March, A-April, M-May, J-Jun).

	RMSE (°C)				SPRD (°C)			
	M	A	M	J	M	A	M	J
				Tmin				
Groß-Enzersdorf	2,9	1,6	1,0	0,8	1,2	1,1	0,9	0,7
Rimski Šančevi	1,3	1,2	1,0	1,6	1,2	1,2	0,9	0,7
				Tmax				
Groß-Enzersdorf	5,1	4,0	2,4	2,8	1,5	1,4	1,3	1,3
Rimski Šančevi	3,0	1,9	1,7	1,5	1,7	1,4	1,4	1,5

The high skill of the MWFs in forecasting low temperatures, especially in spring, is promising from the point of view of predicting frost. Namely, in years with significant shifts of phenological phases to earlier times, frost prediction and protection has become a challenging problem. The comparatively poor performance of the MWFs in forecasting high temperatures in the case of Groß-Enzersdorf results from one warm advection episode that is not simulated by the forecasting model. This outcome most likely results from the difference in altitude between the model grid points and the exact location of the weather station (Lalic et al., 2017).

1.4.3. An application of long-range forecasting

1.4.3.1. Long-range forecasting

Over the past decade, the ECMWF has developed a system for producing ensemble seasonal forecasts based on the same system of hydrodynamic equations used in medium-range forecasting. In this system, perturbations are used to create initial conditions for the ensemble runs. Seasonal forecasting is justified by the long time scale of oceanic circulation (on the order of several months) and by the significant impact of variability in tropical sea surface temperatures on atmospheric circulation globally. Because the oceanic circulation is a major source of predictability on a seasonal scale, the seasonal forecasting system is based on coupled ocean-atmosphere integrations. Seasonal forecasting is also an initial value problem, but much of the information is contained in the initial state of the ocean. On seasonal timescales, the main source of predictability is the coupled ocean-atmosphere El-Niño Southern Oscillation (ENSO) phenomenon (Wu et al. 2009). Seasonal predictability is also thought to arise from the interactions between the troposphere and stratosphere that are associated with the quasi-biennial oscillation (QBO) (Baldwin et al. 2001) and sudden stratospheric warming (SSW) (Marshall and Scaife 2010).

The seasonal forecast system of ECMWF begins with 10 ensemble members (EMs) in 2006 and progresses to 50 EMs in 2014 to produce 7-month forecasts. For the practical use all ensemble members must be included in analysis.

1.4.3.2. Application to agrometeorology and crop modelling

In application ensembles of seasonal weather forecasts as the meteorological inputs to a crop model are used and the initial soil or crop conditions are not perturbed. The methodology used to produce ensembles of crop model outputs is presented and tested for accuracy in Lalic et al, 2017.

The selected case study is for winter wheat growth in Austria and Serbia during the period of 2006–2014, as simulated by the SIRIUS crop model.

The differences between the observations and the forecasts are particularly pronounced in 2010 and 2014 at NS, mainly because precipitation is greatly underestimated in 2010 and 2014 (Figure 4). During the period from March 1 to August 31, 2010, extreme precipitation events occurred. The observed precipitation at Novi Sad (Figure 4 up) is 655 mm, and the average annual precipitation is 647 mm at NS. Most of this precipitation occurred from May to August, and the monthly precipitation values exceed the average monthly values by >50%. In the spring and summer of 2014, precipitation well above the climatological mean was observed, and extreme flooding occurred in Serbia. Even the accurate, ECMWF-issued medium-range forecasts that cover that particular event are not reflected in the long-range forecast, primarily because of the long time series of the climatological values (Lalic et al. 2017).

SIRIUS is run using input data derived from observations, the control run (CR) and the ensemble weather (EA) to obtain ensemble

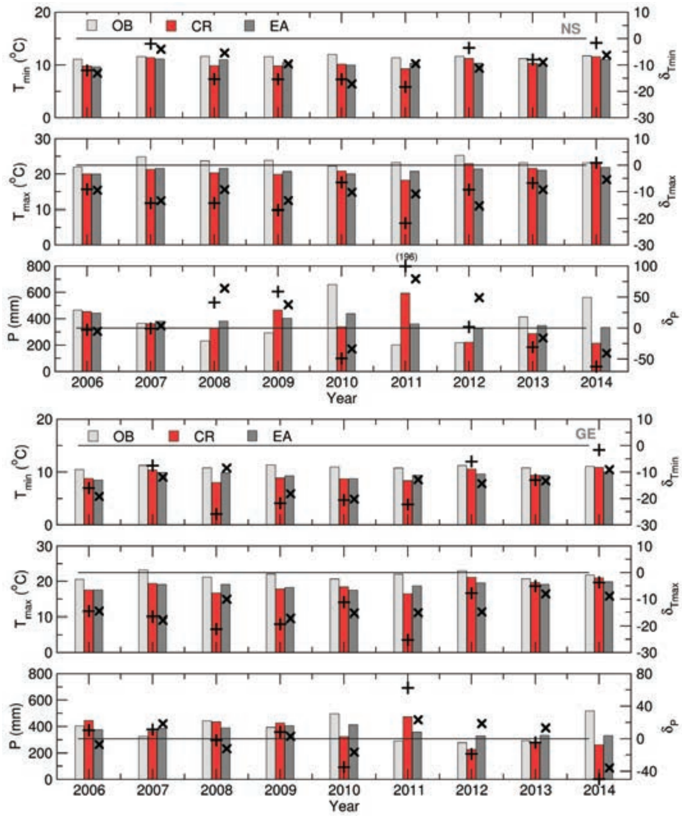
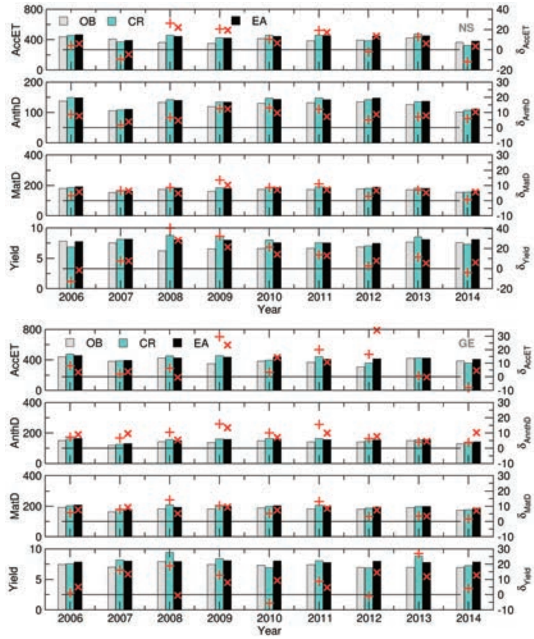


Figure 1.30 Tmin, Tmax and P for 1 March–31 August. The average values (bars) and relative deviations ('+', CR; '×', EA) obtained using the OB, CR and EA datasets for NS (up) and GE (down) for 2006–2014 (Lalic et al, 2017.).

estimates of the selected crop model outputs (Figure 5). The differences in the simulated timing of the anthesis day (AnthD) and the maturity day (MatD) using EA and CR are negligible for both locations, most likely because the summation of air temperatures reduces the effects of small underestimates and overestimates in the forecast values. However, slightly better results are observed for AccET (7/9 at NS and 5/9 at GE), yield (5/9 at both locations), GWF (6/9 at NS and 7/9 at GE) and MaxD (7/9 at NS and 8/9 at GE) (Lalic et al. 2017).

In another case, SWF is used to forecast the green water components, crop yields and green water footprints (WFs) on seasonal scales for selected summer crops (Lalic et al. 2018). Version 5.0 of the AquaCrop model is used in the present study to calculate the intensity of soil surface evaporation and crop transpiration (the sum of both fluxes is taken to indicate crop evapotranspiration in mm day^{-1}) (Figure 6), the water productivity for yield (WPet; i.e., the yield produced per unit volume of evapotranspired water in kg m^{-3}) and the yield (t ha^{-1}). Spring barley, maize and sunflower are chosen for this study. AquaCrop has been previously calibrated and validated for agroecological conditions in Serbia and Austria for the given crops.

Figure 1.31 Yield (t), MatD (DOY), AnthD (DOY) and AccET (mm) (bars) and their relative deviations ('+', CR, '×', – EA) calculated using the OB, CR and EA datasets for NS (up) and GE (down) for 2006–2014 (Lalic et al. 2017).

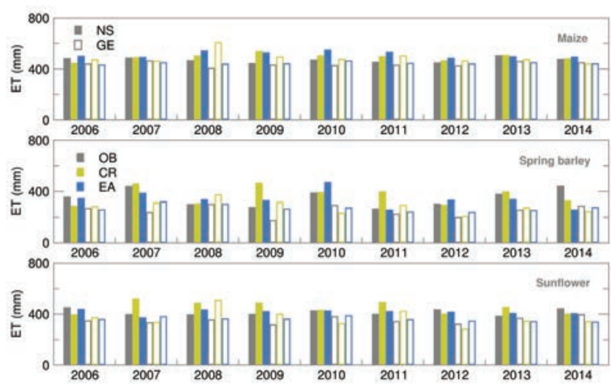


For further results, see Lalic et al. 2017 and Lalic et al. 2018.

The study shows that, although some uncertainties remain, SWFs can potentially be applied in agricultural decision support, especially through their implementation in operational monitoring and warning systems. For example, at the policy level, they can help to improve regional seasonal yield forecasts, forecasts of upcoming risks of crop damage (caused by, e.g., periods of drought and extreme heat) or to establish policy measures in managing irrigation water in advance.

The weaknesses related to extreme weather events can be overcome by using monthly and short-range NWPs during the integration period of SWFs and by improving the ability of crop models to simulate plant development, as well as the risks to crops caused by adverse weather conditions.

Figure 1.32 Evapotranspiration (ET) during the growing seasons of maize, spring barley and sunflower obtained using the observed (OB), control run (CR) and ensemble average (EA) datasets for AquaCrop runs for 2006–2014 (Lalic et al. 2018).



Part 2 – Agrometeorological modeling, soil - atmosphere gas fluctuations, Austrian drought monitoring system, effects of abiotic stress on crop production (drought, excessive salinity and heavy metal pollution)

2.1. Agrometeorological Simulation models AquaCrop model

2.1.1. Agrometeorology

Agriculture was born in the Neolithic period, around 10000 BC, when man realized that with the cultivation of plants it was possible to produce more than necessary to the survival of the community. In particular, agriculture had its first origins in the Fertile Crescent (northern Mesopotamia, South Eastern Anatolia, Palestine), where the first plants cultivated were just the cereals, including barley, millet, wheat. Already at that time, the first human intervention to improve the production of cereals was the genetic selection. The starting point was, in fact, from wild plants with fragile ears adapted to the spontaneous propagation but unsatisfactory from a production point of view. Then, the man began to choose and pick only the best plants, with strong ears and full of grain encouraging, in fact, a pathological character of the plant that led to the loss of self-propagating capacity and to the dependence on artificial seeding.

This was the beginning of a continuous evolution of agricultural activities, that nowadays continue through scientific research and innovative applications, such as genetic improvement, new production methods (digital agriculture), fertilization, machinery, etc.

Despite that there is something that farmers, and scientists, should always consider in order to save, stabilize or enhance their production: climate and weather. Agricultural production, in fact, is highly dependent on the weather conditions.

Agrometeorology, or agriculture meteorology, is the science that studies the interactions of meteorological and hydrological factors with the agricultural-forest ecosystem and with agriculture, understood in its widest sense. It deals with crop (and animal) husbandry, from tillage to harvest.

Among the main variables affecting agriculture and, more specifically, crop growth, development and production are:

- ✓ Solar radiation
- ✓ Temperature
- ✓ Humidity
- ✓ Rainfall
- ✓ Evapotranspiration

Table 2.1. Relations existing between meteorology and agrometeorology. Source: *Prasada Rao, Agriculture meteorology*

METEOROLOGY	AGROMETEOROLOGY
It is a branch of atmospheric physics	It can be considered either a branch of applied meteorology, or a branch of agriculture
It is weather science	It is a product of agriculture and weather science
It is a physical science	It is a biophysical science
Weather service is the concern	Advisory service to the farmers is the concern, based on weather forecast
It is a linking science to society	It is a linking science to the farming community

Solar radiation can be considered as the engine of the entire system. The energy balance, which is the result of the balance between incoming (shortwave) and outcoming (longwave) radiation, regulates the dynamics of all the other meteorological variables.

Besides that, solar radiation directly affects plants as it is the main driver of photosynthesis. Photosynthesis, in fact, changes sunlight into chemical energy, splits water to liberate O_2, and fixes CO_2 into sugar which is the base of biomass accumulation.

Solar radiation also affect plants through photoperiodism, which regulates the winter dormancy of the buds, the fall of leaves, the formation of bulbs and tubers, the determination of sex in dioic plants, and the flowering.

The second important variable, which is correlated to solar radiation, is air temperature. Temperature is one of the most important variables as it affects two phenomena fundamental in biology: the speed of biochemical reactions and the speed of the energy transfer. All chemical, physical and chemical-physical processes which are the basis of biological reactions in plants depend on temperature. Temperature determines the intensity of vegetal (germination, root absorption, photosynthesis, etc.) and microbial (humification, etc.) reactions. It also affects the speed of plant development, the sex expression, the seed dormancy, etc.

The relation between the plant and temperature is usually analysed by considering the following thresholds:

Optimal: vital function proceeds at the maximum speed

Cardinal: above and below which a function stops, starting again when conditions improve

Critical: above and below which functions and/or organs are permanently compromised

Also, the time required to complete the different development phases (phenology) is function of the total heat received by plants. This relation is expressed by the thermal summation (growing degree days – GDD), that is the sum of daily mean temperature within a specific range of development.

Each species has a base temperature above which GDD start accumulating, and total GDD to complete its cycle from germination to maturity.

Another important variable is moisture. The amount of water vapour that is present in the atmosphere is known as atmospheric moisture or humidity. The actual moisture content can be expressed in different forms.

Absolute humidity is the weight of water vapour per unit of air (g/m^3), it is higher during warmer hours/days as evapotranspiration is higher. It expresses the content of moisture of the atmosphere but it does not give information about how far it is from condensation.

Vapour pressure expresses the water vapour contribution to the atmospheric pressure. Consequently, the content of humidity of the atmosphere can be expressed in terms of (vapour) pressure (Pa, bar). There is an upper limit to moisture present in the atmosphere that is defined saturation vapour pressure, beyond which the excess water vapour condenses into water.

Relative humidity is the ratio of the amount of water vapour that is actually present in air (actual vapour pressure) to the amount of water vapour that air can hold at its maximum capacity (saturation vapour pressure) at a given temperature (%). It assumes its highest values in coldest hours/days (winter months and at night) for its dependence with the temperature in the calculation of the vapor pressure.

Precipitation is any product of the condensation of atmospheric water vapour that falls under gravity. The main forms of precipitation include drizzle, rain, sleet, snow, graupel and hail. IN particular, precipitation occurs when a portion of the atmosphere becomes saturated with water vapour, so that the water condenses and precipitates. Part of the rain percolates below the root zone and part flows away as run-off. This deep percolation and run-off water cannot be used by the plants. In other words, part of the rainfall is not effective. The remaining part is stored in the root zone and can be used by the plants: it is the so-called effective rainfall.

Evapotranspiration is the combined effect of two different processes: **evaporation**, which is the conversion of liquid water to a vapour from wet surfaces, and **transpiration**, which is the loss of water vapour by plants to atmosphere. So, **evapotranspiration (ET)** is the sum of water transferred from the surface to the atmosphere by evaporation and plant transpiration. They are normally considered together as their single measurement is very complex from an operational point of view. Crop evapotranspiration is calculated starting from a reference value multiplied by a specific crop coefficient (Kc) which varies among species and during the crop cycle (Fig. 2.1)

Reference ET (ET0)
Reference surface similar to short, green grass
ET0 reflects the evaporative demand of the atmosphere
Only a function of the weather
Penman-Monteith equation (Rad, T, Wind, RH)

Crop ET (ETc)
ETc = ET0 x Kc
Kc integrates all crop characteristics
Kc reflects optimum conditions, so ETc represents a potential ET
- for that crop
- at a specific stage of growth

One of the main uses of measured or estimated agrometeorological parameters is related to agrometeorological crop growth models. Such models, in fact, through the implementation of appropriate algorithms and equations, are able to simulate the different process of crop growth and development with important operational results (Fig. 2.2).

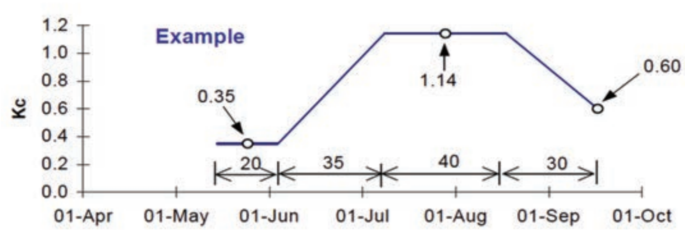


Figure 2.1. Variation of a generic crop coefficient (Kc) during the crop cycle.

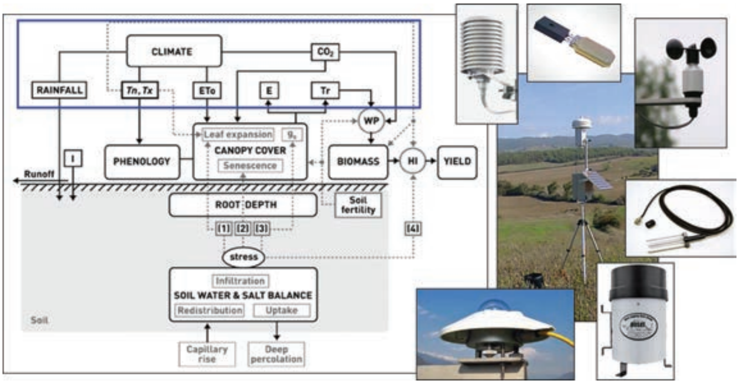


Figure 2.2. Scheme of a simulation model in which agrometeorological variables represent the main input.

2.1.2. Simulation models

A model is a simplified representation of a system. A system is a well-defined part of the real world. In agriculture, a system can be, for example, a crop with all its organs (roots, stems, leaves) and its processes and mechanisms (growth, development, photosynthesis, transpiration, etc.), or the development of a pathogen and its negative effects on a crop. So, the first step for developing, or using, a simulation model is to identify the system in which we are interested.

The construction of a model consists in the identification of a series of mathematical equations by which it is possible to reproduce in the most faithful possible way the behaviour of the examined system. The main advantage is related to the possibility of applying models under agricultural conditions, cultivation and management different from those where models were developed.

Simulation models are widely used by agricultural scientist and it exists an extensive literature on different existing models, their structure and their research or operational applications. Nevertheless, there is always a certain debate between experimentalists and modelers about what is most important between experimental trials and data collection and model application.

Experimental science is guided by the scientific method, already introduced by Galileo Galilei. The scientific (experimental) method implies to make observations, collect information, formulate hypotheses about why things are the way they are, deriving predictions and carrying out experiments based on those predictions. It is a very rigorous method which is required in order to prove the validity of a research. Nevertheless, each time that a measurement is taken, there is a series of steps including the determination of experimental design, the collection, storing, and analysis of samples, the processing of data and finally their interpretation. For each of the mentioned step it is possible to make a mistake and, above all, it is long and time consuming process.

But the reality, especially when agriculture is concerned, implies the need of quick information (near real time) about what is happening in a given situation or what will change in the system as a result of perturbative events (scenario analysis). Also, there are usually limited resources for direct observations (especially on regional scale assessments). For these reasons, it is always more and more difficult to find (good) data of experimental agriculture. Even if simulation models cannot substitute the scientific method, in many situations they can be a very useful tool to support scientists, in particular when:

The states of the system may not be observable, or only with extreme difficulty

Traditional experiments can damage the system

The conditions that you want to test may not be practicable

The time required for experiments can be very long, or experiments can be very expensive

The number of conditions to be evaluated can be very high

Simulation models have a wide range of application, among which:

- Crop growth and development
- Crop productivity
- Water balance
- Protection from environmental adversities (extreme events, drought, etc.)
- Protection from biological adversities (pests and diseases)
- Climate change
- Generation of missing data
- Spatial and temporal interpolation

General benefits of simulation models include a better understanding of physical and biological processes, the organization of the available knowledge and identification of gaps and future research objectives, the manipulations on the real system to test hypotheses about how it works, the evaluation of possible external interventions to change the behavior of the system, and the application as a didactic tool to illustrate the structure and behavior of the system.

On the other hand, the limited procedures of verification and validation, the lack of reliable input, and the excessive expectations in respect of the benefits, especially in relation to an application without the control by experts in the field, are the main critics to an excessive use of models.

Simulation models can be classified in different ways (Fig. 2.3).

Empirical and mechanistic models

Empirical models describe in a simplified way the behavior of a crop. The development of an empirical model is based on the identification, starting from experimental data, of one or more mathematical equations able to represent the process examined. A typical example is the curve of biomass accumulation (dry weight) in crops. Such models are very simple and they require a few inputs, but they not explain any mechanism of the simulated system. For this reason, their use is usually limited to the conditions in which they have been developed.

Mechanistic models describe and explain a specific phenomenon based on the fundamental mechanisms that govern the functioning of the system. For example, the increase of the dry weight can be described by a series of more complex functions, each of which takes account of smaller sub-processes, such as the influence of the ecophysiological characteristics of the species on light interception, on photosynthetic process, on the production of assimilates and, therefore, on the increase of dry weight. The resulting pattern is quite complex, but (theoretically) able to predict the growth of a plant regardless the environmental conditions.

Static and dynamic models

Static models represent relationships between variables that do not change with time, and then you know the final value only and not the trend over time (e.g. *regression models*)

Dynamic models contain the time as an explicit variable. Describe the way in which the system changes over time (e.g. *disease simulation models*)

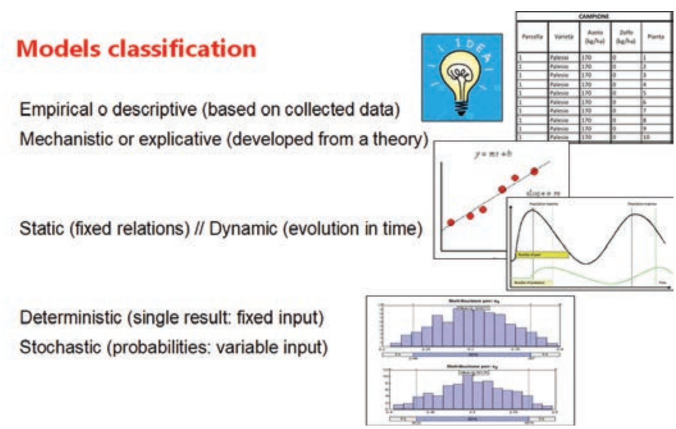


Figure 2.3. Main classifications of models

Deterministic and stochastic models

Deterministic models make a prediction providing as output a numeric value without giving any measure of its probability distribution. The input variables assume fixed values. It does not take into account the uncertainty associated with the input variables

Stochastic models (stochastic = due to chance, random) take into account the variations (causal or not) of the input variables, and then provide results in terms of "probability".

It is important to emphasize that what differentiates the deterministic models by stochastic ones is that in the latter is taken into account the variability of the input data.

Simulation models and experimental data are intimately related; in fact, a model cannot be developed and its performances cannot be assessed if good experimental data are not present. In particular, beside the model development itself, which is not treated in this document, calibration and validation are the two procedures in which experimental data are required.

Calibration, is the procedure through which one or more series of experimental data is used to formulate the model, to compare the data obtained with the experimental reality, to eventually reformulate the model structure or adjust some parameters.

Validation is the procedure by which you compare the simulated data from the model with experimental data not used in its development to identify the accuracy and precision of estimates (Fig. 2.4).

Credits

Part of the teaching material of this section has been adapted from various lectures of Prof. Roberto Confalonieri, of the University of Milano, Italy.

2.1.3. AquaCrop model

AquaCrop is a crop water productivity model developed by the Land and Water Division of FAO (Food and Agriculture Organiza-

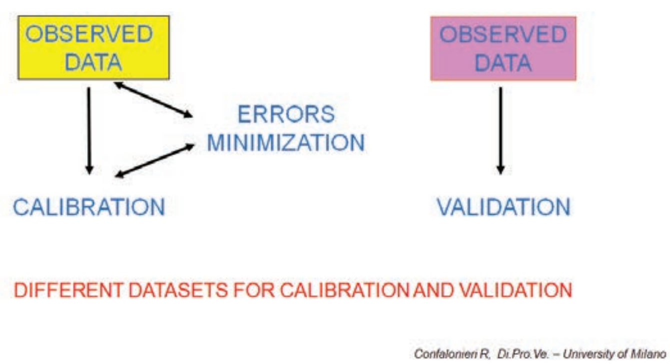


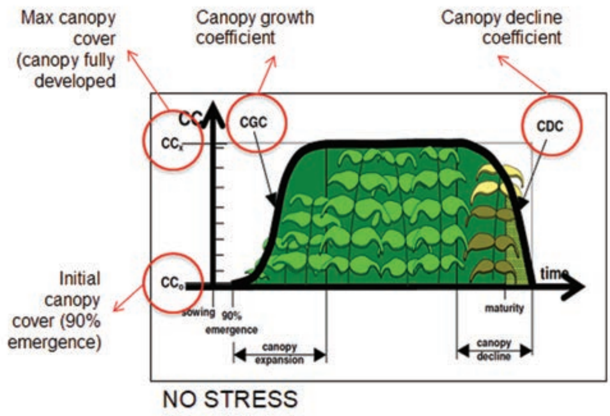
Figure 2.4. Calibration and validation procedure. The first used to minimize the errors of the model, the second used to measure the model performances once it is calibrated.

tion of the United Nations). It simulates **yield response to water** of herbaceous crops, and it particularly addresses conditions where water is a limiting factor in crop production. Nevertheless, as water availability is becoming a critical issue in many regions (included Europe) due to climate change and to natural resources overexploitation, AquaCrop is becoming a reference model used for guiding irrigation management in agriculture. One of the main strength of AquaCrop is the good balance between accuracy, simplicity, and robustness. It uses a small number of parameters and input variables that can be easily determined in the filed or obtained from specific databases, nevertheless it is able to accurately simulate crop physiological processes and soil water budgeting processes. Moreover, it is freely available on web together with exhaustive documentation, training modules and tutorials. For all these reasons, it is particularly suited not only at research level but also for practical applications. Among them, AquaCrop can be used to predict crop production under different water-management conditions (including rain fed conditions, supplementary, deficit and full irrigation) or different climates; to optimize crop planning and management and developing irrigation strategies under water deficit conditions; to optimize crop water productivity; to compare different scenarios; to analyze yield gaps or impacts of climate change.

In general terms, a model is a simplified representation of a system, is a well-defined part of the reality. The system considered by AquaCrop is the crop-soil interaction system with its upper (atmosphere) and lower (depth and quality of water table) boundaries conditions able to affect such interactions. In fact, the core of AquaCrop, which is the water productivity equation, is inserted in a set of additional components: SOIL, with its water balance; CROP, with its processes, and ATMOSPHERE, with temperature, rainfall, evaporative demand and CO_2 concentration. Also, field management factors are considered (irrigation, surface management, soil fertility) as they can affect water balance, crop development and therefore, final yield.

AquaCrop simulates crop yield in four steps: crop development, crop transpiration, biomass production and yield formation. AquaCrop uses green canopy cover (CC) to describe foliage development, intended as the fraction of soil surface covered by the green canopy. In optimal conditions, canopy development is described by a few parameters: knowing the moment in which the maximum CC is reached the model simulates the canopy development between germination and that moment through a logistic equation. Then, at the end of the season when senescence occurs the CC declines. As mentioned, this describes the process under non-limiting conditions (Fig. 2.5).

Figure 2.5. Crop development under non-limiting conditions. Source: AquaCrop Reference Manual, www.fao.org/nr/water/aquacrop.html



Nevertheless, this development can be limited by stress factors. AquaCrop considers the root zone as a reservoir in which the content of water varies depending on input (rainfall, irrigation, capillary rise) and output fluxes (runoff, ET, deep percolation). If water is non-limiting factor, its content increases above field capacity. In absence of water inputs, the content of water drops and the crop become under stress. When wilting point is reached, the crop dies.

To describe the effect of water stress, the model considers different thresholds. The first is the threshold for leaf canopy expansion (blue): when the water content drop off this threshold the crop start to be under water stress and the crop develops slower than under non-limiting conditions. The second threshold is canopy senescence (yellow) close to the WP. If the water drops below this threshold, the canopy starts to die. Then, based on daily water balance, AquaCrop simulates the actual crop canopy development.

Second step of simulation is crop transpiration. To simulate crop transpiration AquaCrop uses the Kc ET0 method, determined only by weather conditions. ET0 is the reference evapotranspiration and represents the evaporating power of the atmosphere, Kctr is a coefficient characterizing the transpiring crop, and it is proportional to CC: if CC is small, Kc is small and transpiration is limited. The proportional factor between Kc and CC depends on the type of crops and express how my transpiring crop differs from the reference grass. This is how Tr is calculated under non-limiting conditions. So, knowing the canopy cover now the model simulates the crop transpiration by multiplying the ET0 with a Kc factor which is proportional to CC. Nevertheless, water stress can occur and this lead to stomata closure. This is simulated once again by computing the soil water balance. Beside the two thresholds already described, there is an additional threshold which is the one for stomata closure (Fig. 2.6). When the water content drops below the red line, stomata start to close and transpiration is reduced. This is simulated throu-

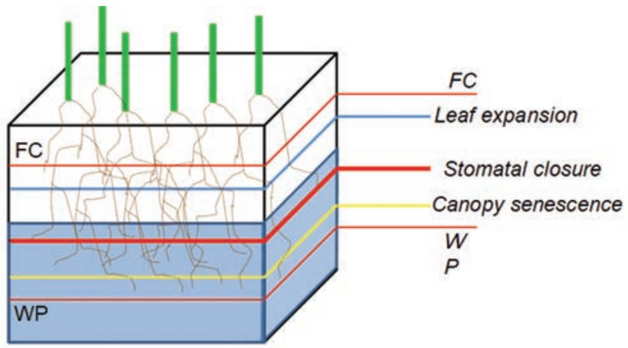


Figure 2.6. The root zone with the different threshold affecting canopy cover and transpiration. FC: field capacity; WP: wilting point. Source: AquaCrop Reference Manual, www.fao.org/nr/water/aquacrop.html

gh a water stress factor, Ks factor ranging between 1 and 0. When the water content drops below the red line, Ks becomes smaller than 1 and transpiration is reduced. When WP is reached, Ks becomes 0 and transpiration stops.

The third simulation step is the biomass accumulation. Plants take up CO_2 through stomata and by photosynthesis the CO_2 is converted into carbohydrates which are the bricks of the biomass. So, there is a direct relation between crop transpiration and biomass accumulation: if the crop is well developed and water is abundant, a lot of water will escape through the stomata and at the same time a lot of CO_2 can be absorbed. When the crop is small or there is water stress, transpiration is reduced and also biomass accumulation is limited. The relation between biomass production and transpiration is expressed by the Water Productivity (WP). WP gives the slope of the line of the transpiration - biomass curve. For different crops the relation between biomass production and transpiration is linear, but the slope of the line (WP) is different. This slope differs between different crops but also between different climates. For this reason, AquaCrop normalized WP for the climate. This normalization is done by dividing the daily amount of water transpired by the daily ET0. In this way linearity is still there but slopes changed compared to not normalized WP, and crops results grouped in C3 (lower WP) and C4 (higher WP) (Fig. 2.7).

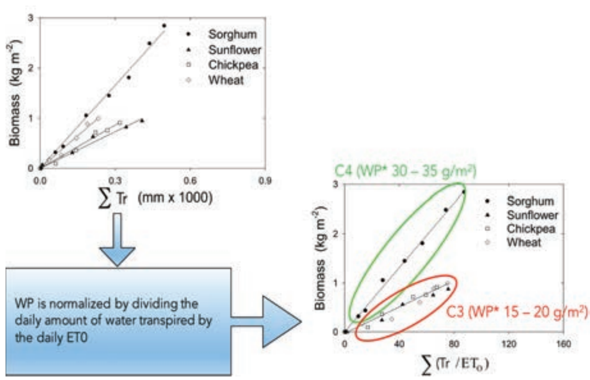


Figure 2.7. Relation between crop transpiration and biomass accumulation. Source: AquaCrop Reference Manual, www.fao.org/nr/water/aquacrop.html (modified)

The last step is the simulation of yield formation. By using a harvest index (HI) the fraction of the biomass that is the harvestable product, crop yield is obtained by the biomass. During the season HI can vary from its reference value and this variation depends on the timing and on the extent of the water and heat stress.

AquaCrop, by calculating the daily soil water balance and adjusting the water content in the soil profile, is able to detect stresses that might develop in the root zone. When a soil water stress is detected, leaf expansion, crop transpiration and biomass accumulation, and therefore the dry yield are then affected and the impact on the final production depends on the timing and the extent of the occurred stress (Fig. 2.8).

In AquaCrop, crop growth can be affected by different stress factors: water, temperature, soil fertility and soil salinity. The effects of these stresses are described by stress coefficients Ks. Ks is a modifier of its target parameter and varies between 1 (above the upper threshold) when stress is absent, and 1 (below lower threshold) when the effect of stress is maximum. The magnitude of the effect on the process is described by the shape of the curve and by the relative stress.

Credits

The teaching material in section 2.2. has been adapted from:

- http://www.fao.org/aquacrop
- **© FAO, 2011. AquaCrop Reference Manual. Chapters 1-2-3**
- http://www.fao.org/nr/water/aquacrop.html

More information on the AquaCrop, as well as full documentation, trainings and video tutorials can be found at *http://www.fao.org/land-water/databases-and-software/aquacrop/en/*

Also, notice that a new Open Source version of AquaCrop (AquaCrop – OS) was released and it is available for download. For more information, refer to: *Foster et al. (2017). AquaCrop-OS: An open source version of FAO's crop water productivity model. Agricultural Water Management 181: 18–22.*

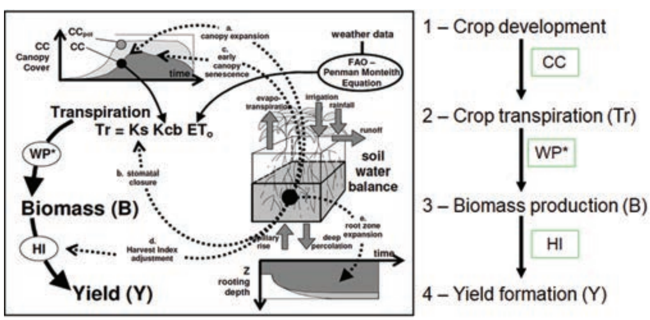


Figure 2.8. The calculation scheme of AquaCrop summarizing the 4 simulation steps. CC: canopy cover; WP*: normalized water productivity; HI: harvest index. Source: AquaCrop Reference Manual, www.fao.org/nr/water/aquacrop.html (modified)

2.2. Greenhouse gases and ammonia emissions from soil

2.2.1. Introduction

In the last decades, agricultural productivity was intensively increased following world human population growth and food demand. If on one hand croplands increased by 27% on the other hand, agricultural productivity increased by 135% (intensification) (Burney et al. 2010; Tilman et al. 2011). This was due to the increased adoption of external inputs as mechanization and chemicals. In addition, due to the easy availability of fossil energy source, their high net energy potential and the relative cheap prices, a great increase in their use occurred during the last century. Agriculture, in this regard, mainly took advantage from fossil energy sources from chemical (fertilizers, herbicides/pesticides) and mechanical (machinery) inputs. However, the intense use of those fossil energy sources had led to a fast reduction of them together to an increase of environmental impact from modern agriculture mainly related to greenhouse gases (GHGs) emissions. The direct impact of exponential increase of GHGs as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) emissions is essentially related to their contribution on the Global Warming of Earth's surface that improved global surface temperature by 0.85°C in the last 130 years (IPCC, 2014). Global Warming Potential (GWP) is a factor that express the impact that each gas have on the absorption of energy into the atmosphere, the slowing on the rate of energy that escape from Earth to the space and their permanence into the atmosphere. The first two factor are also known as "radiative efficiency" and the last as "lifetime", both contribute on the definition of GWP of each gas. GWP was developed to make a comparison between different gasses. It measure how much energy is absorbed by 1 ton of gas, over a given period (usually 100 years), compared to 1 ton of CO_2. The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period (EPA, 2017). In this regard, on a lifetime of 100 years CH_4 show a GWP of 25 and N_2O show a greater GWP reaching 298 value compared to CO_2. Nowadays, following the directives of Paris Agreement (2015) the reduction of GHGs emissions and mitigation of Global Warming are fundamental issues at global level adopted by several countries. Agriculture, in this way, may contribute on the reduction of human activities impacts on the environment adopting more sustainable management strategies to minimize inputs and preserve fertility of soils. In this regard, agriculture potential on Global Warming mitigation is represented by GHGs reduction. More than GHGs, ammonia (NH_3) represent one of the main emitted gas by agriculture contributing of 50% of global emissions and 90% of European emissions (Carozzi et al., 2013) with indirect impacts on the environment. NH_3 is one of the main responsible factors of acidifying and eutrophication because the deposition of NH_3-derived compounds causes acidification of soil (Asman et al., 1998) and natural water resources (Sutton and Fowler, 2002). Moreover, NH_3 is considered an indirect GHGs because is a precursor of N_2O (Moiser, 2001) and its presence in atmosphere is strictly related to fine particulate matter production. In general, GHGs emissions from agriculture mainly came from three sources as soils, enteric fermentation and manure management; the other two sources that affect global GHGs agricultural emission, as burning of agricultural residues and rice cultivation, have only minor contribute in Europe (Eurostat, 2015). Several strategies are proposed and adopted for the reduction of agricultural impacts and, due to its high weight on the environment, fertilizer sector is one of the main studied.

2.2.2. Global Carbon dynamics and emissions from agriculture

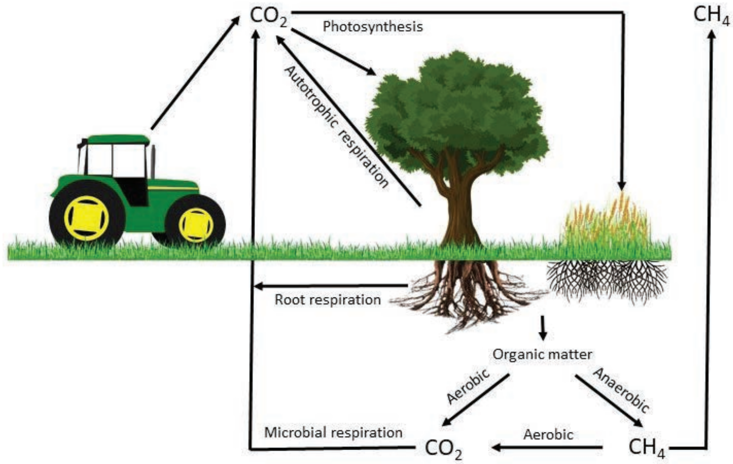
Carbon (C) represent the basis for life on the Earth and it is the primary structure for all living organisms. The main global C pools are soil, oceans and atmosphere and the exchanges between those pools represents the C budget. The global C balance is the balance of exchanges (input and output) between those pools or between a specific cycle. The evaluation of C balance of a pool can provide information if this is a source or consumer of CO_2.

Autotrophic organisms are both consumer and pool of C because they use CO_2 for their metabolism (photosynthesis) and stocks the C in their tissues. On the contrary, heterotrophic organisms obtain C for their metabolisms from autotrophic ones and stocks C in their tissues. However, heterotrophic organisms represent a source of CO_2 as byproduct of cellular respiration. Based on the presence/absence of O_2 different cellular respiration occur: in presence of O_2, aerobic respiration occurs and CO_2 is produced as first byproduct. On the contrary, when the great part of soil pores are full of water and there is a lack of O_2, anaerobic respiration occurs and CH_4 is produced as byproduct of the process. Nevertheless, when all the living organisms dies, C included in their tissues is degraded and move to a different pool (soil and atmosphere). C rate that is stocked into the soil follow several transformation from less to high stable forms. One of the most important stable form of C for autotrophic is represented by organic matter. However, crop uptake and agricultural management, as tillage, reduces its amount into the soil. In particular, the increase in soil pores and aeration following tillage, accelerate soil organic matter mineralization with a net production of CO_2. However, an additional factor of high-stable C compounds into the soil is represented by oil that is still the basis of global energy sector with great amount of CO_2 emissions.

Certainly, CO_2 is the main GHG from human activities, and agriculture, accounting for 60 % of the total greenhouse effect. From the industrial revolution to the present, atmospheric concentration of CO_2 raised from 280 ppm to 390 ppm. This intensification on CO_2 emissions is mainly attributed to the change in land uses, deforestation, burning of non-renewable fossil energy sources, forest fires etc. Following this growth in CO_2 emissions, more and more attention has been dedicated on GHGs emissions and environmental impacts of human activities. In particular, a specific attention was dedicated to those strategies that ensures the achievement of high level of environmental sustainability. In this way, traction sector represent one of the main factor of atmospheric pollution and the use of renewable energy sources instead of fossil fuels has gained considerable interest. In agriculture, the reduction of CO_2 emissions is mainly due to the adoption of efficient farming practices as the reduction of the use of mineral fertilizers, crop rotation, the reduction of pesticides and herbicides. In particular, in agriculture CO_2 is mainly produced by respiration and combustion processes. As byproduct of respiration, CO_2 is largely produced by agricultural soils from roots respiration, aerobic and anaerobic microbial respiration. Roots respiration produces roughly 50% of the total soil respiration (but it may change between 10 and 95% based on crops). In addition, ecosystem respiration contribute on CO_2 emission dynamics and it includes aboveground plant respiration. The difference between photosynthesis and ecosystem respiration represents the Net Ecosystem Exchange (NEE) and provides information about the fate of C into and ecosystem. A positive NEE reveals a C source, on the contrary, negative NEE represent a C sink. Moreover, CO_2 represents one of the main byproduct of combustion that in agriculture occur from tractors. In this way, the adoption of more efficient farming practices as minimum tillage, sod seeding and crop rotation highlight a great potential of CO_2 emissions reduction. In the last few years, an additional agricultural strategy has gained specific attention for the high potential on the reduction of external inputs and agricultural impacts on the environment: *precision farming*. The main principle of precision farming is to provide what it needed where it needed optimizing returns on inputs while preserving resources. In this way, the use of tractors and external inputs is minimized with a positive effect on the environment.

However, more than CO_2, agricultural systems are responsible for the emissions of another source of carbon that is represented by CH_4. It is mainly produced by enteric fermentation of livestock (around 40% of total GHGs emissions from agriculture) and from paddy lands (11%). Nevertheless, CH_4 is also produced from all agricultural soils as last step of organic matter degradation in anaerobic

Figure 2.9. Carbon emission dynamics from crop-soil systemsa



conditions from methanogenic microorganisms. Produced CH_4 move to the atmosphere through three main ways:

- diffusion, through soil pores
- aerenchyma tissue of specific crops (e.g. rice). In particular, those crops has modified their morphology to create a whole space into the tissues for gas transport
- boiling, when soil water is saturated by methane and gas is emitted as bubbles.

However, when oxygen (O_2) content of soil increase, CH_4 production decrease due to develops of aerobic bacteria community (methanotrophic). In particular, those kind of bacteria are able to use CH_4, and O_2, for their metabolism with CO_2 production. Generally, natural CH_4 production follow a seasonal trend based on soil temperature, soil water content and presence/absence of crops. Permanent wetlands are natural source of CH_4 during all the year, on the contrary dry ecosystems are natural sink of CH_4 that is mainly used from aerobic bacteria for their metabolism. Those ecosystems that show an alternation between wet and dry periods are both sink and source of CH_4. Adoption of the best agricultural management strategies that ensure a correct drainage of soils is an effective method to reduce CH_4 emissions.

2.2.3. Global Nitrogen dynamics and emissions from agriculture

Nitrogen (N) represent one of the main factors of soil fertility and is the basis of a wide range of biological compounds. For this reason N represent the most important element in crop fertilization and its presence/absence in soil represent one of the main factor that affect crop growth and yields.

Atmosphere represent the main pool of N with a concentration of approximately 78% of total gases. In atmosphere, its elemental form (N_2) represents the great part of N. However, N_2 is not available for plants that need chemical transformation to convert it in a solid form into the soil. The main process of gaseous N transformation is *Fixation*. N fixation is a reductive reaction developed by bacteria and green algae that convert N_2 in ammonium (NH_4^+) that is quickly used in amino acids production. Nitrogen-fixing microorganisms can be identified into two different categories: free-living (nonsymbiotic) and mutualistic (symbiotic). The first are responsible to the fixation of lower amount of N into the soil (10-20 Kg/ha/year). Mutualistic N-fixing microorganisms creates a relation with plants with an exchange of nutrients. In particular, plants provides mainly carbohydrates for microorganisms metabolism while them develops N-fixation providing N-easily available compounds for plants. Mutualistic N-fixation is the most important in agriculture due to the high amount of N converted from N_2 to NH_4^+ (60-250 Kg/ha/year). In this way, leguminous crops and *Rhizobium* bacteria represent the most effective mutualistic relation between microorganisms and plants. NH_4^+ production process is called *ammonification* and is followed by nitrification process that convert NH_4^+ in nitrates (NO_3^-) that are another category of easily available N compounds for crops. In parallel to N fixation, external N supply represent an important factor on N budget in ecosystems. It can be natural, from degradation of organic matter (dead plants and animals), or human-induced, through fertilization. However, plants use not all the N that reach the soil. In particular, the main factors of N losses are represented by leaching, following irrigation or rainfall, and volatilization. If leaching concern mainly NO_3^-, volatilization is a process that may affect a wide range of N forms. In particular, volatilization may occur during hydrolysis of NH_3-based compounds (urea is the first fertilizer of this category) with NO_3^- production. Summer high temperatures and average amount of water into the soil strongly encourage this process. Moreover, hydrolysis process has an additional impact on the environment due to CO_2 production as byproduct of the reaction. However, hydrolysis is a process that occur on manure during manure and slurries storage or spreading in field. For this reason, livestock systems are one of the main factor affecting NH_3 emissions from agriculture.

The most important dynamics that affect N volatilization losses from natural ecosystems is represented by denitrification. Denitrification is a process that take place under anaerobic conditions by a specific group of bacteria. Those bacteria use NO_3^- as final electrons acceptor during anaerobic respiration. Denitrification produce N_2, N_2O, NH_4^+ and nitrite (NO_2^-). However, reduction of NO_3^- to NH_4^+ and NO_2^- are reversible reaction. For this reason, denitrification N losses are referred just to those reaction that produce atmospheric N losses on the elemental form (N_2) and oxides (N_2O).

Denitrification represent a negative process due to the permanent N losses from the biogeochemical cycle into the soil, and so crops. Because denitrification require anaerobiosis conditions, the most sensitive soils are those who present frequent flooding and bad structure conditions. The adoption of irrational soil tillage and inadequate water management strategies may aggravate this situation.

2.2.4. Factors affecting GHGs and NH_3 emissions

Humidity

Soil humidity is the single most important soil parameter for soil gas emissions, since it controls microbial activity and all related processes. If from one hand N_2o production find its optimum at approximately 60% of soil pores filled by water, CH_4 require strictly anaerobic conditions and correlates positively with soil humidity. Grain-size distribution influences soil moisture. Soils with a high proportion of large pores retain less water and therefore foster the emission of gases produced under aerobic conditions. Soils with dominant fine pores support the formation of CH_4 and N_2O produced under anaerobic conditions. Higher CO_2 emissions are observed with fine textured soils, especially compared to sandy soils during warm dry periods. Stable soil aggregates (concretions, crusts) lead to lower soil emissions since C and N are less available for soil microbes. Precipitation after extended dry periods causes the pulsing or "Birch effect": emissions increase within some minutes or hours after the onset of precipitation and return to background levels within a few days. This is driven by the renewed mineralization and the availability of easily decomposable materials for the metabolism of reactivated bacteria community. However, the Birch effect decreases with higher frequencies of wet–dry cycles.

Temperature

Soil temperature is important to explain the variations of trace gas emissions from soils. An increase of soil temperature leads to higher emissions and to higher soil respiration rates as a positive feedback response of increased microbial metabolism. CO_2, CH_4 and N_2O emissions are additionally forced by increasing soil respiration rates with increasing soil temperatures, leading to decreasing O_2 concentrations in the soil. The positive temperature effect may be overlain by soil water stress, since water is needed as a transport medium for nutrients required by microbes. Generally, due to the warmer temperatures and increasing soil water content, in continental areas the highest emission rates are observed between spring and summer. During dry summer or cold winters soils highlight the lowest amount of emissions due to the reduced activity of soil microbial activity.

Exposure and air pressure

Site exposure (elevation, morphological position, plant cover) influences soil temperature and moisture. For instance N_2O emissions are higher in depressions than on slopes and ridges due to higher soil moisture. Lower air pressure supports higher soil emissions due to reduced counter pressure on the soil.

Vegetation fires

Fires in ecosystems (and agroecosystems) can affect the GHGs emissions balance of soils, depending on temperature and duration of the fire. Burned areas show lower CO_2 and N_2O fluxes than non-burned reference sites for around one month after burning. This is caused by reduced root respiration in the absence of plant cover and the related pH change. Also lower N_2O emissions occur after fires and are mainly caused by charcoal production. After burning, soil temperatures increase due to missing canopy, while soil moisture does not change since lowered plant transpiration compensates for missing/reduced plant canopy. Few changes occur for CH_4 uptake in soils that is not affected by fires.

Soil pH

pH is a factor that strongly affect soil microbial community and thus, organic matter degradation and emissions. In particular, acidic soil conditions are critical for microbial community and emissions are lower. Except CH_4 that is mainly produced between pH 4 and 7, the optimum level for GHGs emissions is around neutral conditions.

Nutrients

Nutrient availability is fundamental to microbial and plant respiratory processes. Thus, natural N and C content in soil, as well as atmospheric deposition, manure or fertilizer applications play an important role. Based on C/N ratio GHGs emissions follow different trends: CO_2 and CH_4 show a positive correlation with C/N ratio. On the contrary, increasing C/N ratio N_2O emissions decrease. However, this is logical due to the reduction in degradation of organic matter and N availability.

Increasing soil N content generally leads to higher soil respiration and to higher NEE, if carbon is not limiting. With limited C availability, N fertilizer application has limited influence on soil respiration. N fertilization leads to a higher sensitivity of soil respiration against soil moisture and to a lower sensitivity to soil temperature.

To minimize N_2O emissions from agricultural lands, fertilization rates need to be adapted to crop needs since not all forms of N can be taken up by plants. Non crop-available N amounts lead to increasing N_2O emissions. Cover crops increase CO_2 and N_2O fluxes after their incorporation and positively influence soil respiration during their lifetime than bare soil. Reduction of N_2O emissions after fertilization can be achieved using controlled-release fertilizers or denitrification inhibitors. However, this effect can be disturbed by heavy precipitation events. Fertilizers applications are influenced by the soil water content and tillage system. For instance, fertilization with urea produce higher N_2O emissions under no-till and conservation tillage than incorporation of the fertilizer. NH_3 emissions are ensured by the use of ammonium-based fertilizers and this is logical. However, it was observed as the incorporation of fertilizers after spreading strongly reduce NH_3 emissions and N losses.

Vegetation

The presence of vegetation influence soil respiration dynamics and CO_2 emissions. This is due to the combined effect of roots and microbial respiration. Young forests show the highest CO_2 emissions because of the great amount of fine young roots and the abundance of organic matter that strongly encourage soil microbial proliferation. In old forests the reduced roots respiration activities are partially compensated by the high microbial respiration following the great availability of organic decomposable material. In a grassland, a well-balanced ratio of leguminous and C3 and C4 crops resulted in an increased C-sequestration potential. On agricultural sites, N_2O emissions from legume-N were significantly lower than fertilizer-N derived N_2O emissions. Moreover, the presence of vegetation preserves soil water content than bare soil and, when heavy rains occur, may create the conditions for denitrification (N_2O emissions) and CH_4 emissions. However, in normal conditions vegetation may increase O_2 concentration into the soil due to the increased porosity following roots development.

Soil temperatures decrease due to the higher leaf area and related shade.

Land-use change

Land-use change is very important for GHG emissions from soils, especially when forests, grasslands and peat lands are converted to agricultural lands. Within the first years after turning forest into agricultural land, 30–35% of the soil carbon stored in the top soil layers (5-10 cm) is lost.

2.2.5. GHGs and NH3 emissions monitoring systems

GHGs and NH_3 emissions monitoring is fundamental on the evaluation of sustainability of agricultural management strategies. In particular, the investigation on the fate of C and N resources provides fundamental information about the efficiency on nutrients use efficiency of the agroecosystems.

In general, trace gas emissions from soils are being directly measured with chamber techniques and micrometeorological methods, obtained through space and airborne measurements, and calculated with empirical and process-oriented models.

Chamber systems

Flux chamber monitoring is mainly used for gases as CO_2, CH_4, N_2O (and NO). A box or more often a cylinder is placed on soil surface so that the section of its base is open to the ground and emissions accumulate into the chamber headspace. Chambers have to be constructed with non-reactive materials (steel, PVC etc.) so that no interferences occur during measurements. Different techniques can be used on gas emissions analysis but the most widely ones are: gas chromatography, infrared spectrometry (IR), non-dispersive infrared sensors (NDIR), flame ionization detector (FID), chemioluminescence etc. The main differences can be found on the method for sampling collection and analysis. The most modern, and accurate sensors, use a pump system that collect samples from chambers and analyze them directly in field. In general, those sensors require a short time (10 seconds to a minute) to analyze the samples without reagents consumption. Chamber headspace represent an important factor that play a key role on the accuracy of measurements. More headspace is low more accuracy increase. However, gas emissions measurements on crops need chambers that can host crops inside of them. In arboriculture, for instance on grapevines, 2-3 meters height chambers are used for a full evaluation of soil-plant gas flux. Chamber systems can be divided in closed and open chambers, with closed chambers being divided in closed static chambers and closed dynamic chambers. Main differences between open and closed chambers are referred to management because closed chambers, after measurements, need to be removed to avoid saturation of chamber headspace. An exception is represented by automatic closed chambers that perform automatically the close/open phase. However, due to the sophisticated technologies systems and the expensive costs, cheap closed chambers are still the most common systems. The main advantage of open chambers is there are no accumulation times needed, since the flux is analyzed continuously. However, both closed and open should be equipped with auxiliary sensor to evaluate those factors that may affect emission trends from soil: air temperature, air pressure, air relative humidity, solar radiation, soil temperature and soil water content. In general, an increase in temperature and water amount encourage emissions dynamics following a proliferation of bacteria community. Of course, the analysis of nutrients, organic matter and texture of soil provide additional information for a better understanding of bacteria activity into the soil.

Chambers have to be installed on an anchor system (non-reactive materials) to prevent gas leakage from the chamber to the atmosphere. To reduce the influence of the anchors on the soil structure and crop roots, the collar should be embedded to a depth of a few centimeters and, if it is possible, between crop rows. However, some chamber systems may be installed directly on the soil surface without any anchors, yet this is not recommended on forest soils. Closed chamber need an accumulation time before performing measurements. Based on monitored gas accumulation time may change, however an average accumulation time of 60 minutes allow to collect reliable data for all GHGs.

Regardless the adopted method, a specific data analysis is required to obtain reliable information about the flux of each analyzed gas. In this sense, linear regression represent the best method to estimate flux emission on a specific period of interest. Collected data from all chamber system is referred to a variable surface (cm^2). Thus, a conversion to cm^2 to hectare (common surface reference) is needed to obtain reliable data to compare the considered experiment with others or propose guidelines for farmers/stakeholders/politics.

Micrometeorological measurements

Eddy covariance method is a direct micrometeorological approach. It uses vertical turbulences to analyze the turbulent heat and gas exchange between soil surface and atmosphere. A 3-D ultrasonic anemometer system and a gas analyzer combined to a tower of at least 2 meters height are needed for this method. Measurements may run continuously and include areas of up to several square kilometers, the medium local scale. Eddy covariance integrates plants and trees, and thus completely covers soil, biosphere and atmosphere. Point of weakness of the system is an underestimation of the fluxes when turbulence are at the ground level. It is applicable to forest soils and it is recommendable to perform measurements on levelled ground, above or within low-density vegetation. However, data post-processing after collection in field is complex.

Spaceborne measurements

The first method is represented by data acquisition of gas fluxes from satellite that provide information about gas concentration based on the measurement of the intensity of the reflected sunlight in small wavelength bands in the visible and short-wavelength IR portion of the spectrum. However, there is still considerable uncertainty in the spatial agreement of the area and distribution of the relevant land cover types (e.g., grassland, forests, bare soil, crop-land etc.). Either these uncertainties are attributed to a number of limitations that are determined by the technical specification of the sensor (wavelength, spectral and mostly, spatial resolution) or the derived data products (e.g. land cover maps). Differences between land cover maps have important implications on modeling global emissions. Thus, the choice of a map might introduce a significant bias in any regional to global carbon balance model.

Airborne measurements

Airborne methods use direct sampling approaches to collect gases from transects, e.g., over different types of land use or from near-surface environments to higher tropospheric altitudes. There are different methods for air samples collection: ascending and descending flight path of an airplane where samples were stored in flasks and analyzed by gas chromatography in the laboratory. Until few years ago, through some balloons air sampling was performed at different height. The collected samples still needed an additional laboratory analysis phase with increase in economic costs and time.

2.2.6. Modeling soil GHGs emissions

Since measurements deliver only punctual data, modeling GHGs emissions from soils is important to regionalize such measurements and to calculate global budgets. The most widely used models are able to simulate several factors as daily decomposition, nitrification, ammonia volatilization, CO_2 production (soil microbial and root respiration), N-uptake of plants and plant growth. These models are also used to calculate GHGs emissions from soils, especially from agricultural lands. Meteorological and soil parameters (e.g. soil texture, pH, bulk density, organic C etc.) as well as vegetation type and management practices (tillage, fertilizer application, grain yields etc.) serve as important input data. However, models exploit measured input factors to predict a specific phenomenon. So, the more numerous and accurate the data, the more reliable the model is.

2.3. The Austrian Drought Monitoring System for agricultural crops in Austria (AgroDroughtAustria-ADA)

2.3.1. Introduction

Given the considerable uncertainties around projections of climate impacts on agriculture at local and regional scales, there is an evident and urgent need for reliable sciencebased early warning systems providing timely and understandable information for decisionmakers and stakeholders. In the project AgroDroughtAustria, therefore a crop specific drought monitoring system for Austria for operational application was developed with following aims

1) Establish a set of calibrated indicators and methods on crop specific drought and heat vulnerability and impacts based on observed data and crop model application
2) Assess crop drought and heat stress at high spatial resolution by using improved spatial gridded weather parameters input (INCA data)
3) Establish a neartime (up to 10 days) forecasting method for drought occurrence
4) Adapt and validate methods for crop drought and heat stress detection and yield impact implemented in a GISbased operational monitoring system with high spatial resolution (500x500m) for main vulnerable arable crops in Austria

The drought monitoring system **ADA** is designed to be extended by further weather based cropping risks, called **ARIS** (Agricultural Risk Information System). The actual status of the operational monitoring system can be accessed online at:
https://warndienst.lko.at/winterweizen+2500+++6578?typ=RSSC

2.3.2. Description of the AgroDroughtAustria (ADA) monitoring system

2.3.2.1. Gridded weather and forecast input data sets for ADA (ARIS)

ZAMG runs their own nowcasting and weather prediction models in an operational mode to provide weather analysis and forecast data up to 3 days ahead to users. In addition ZAMG has access to forecast data from ECMWF which runs global models targeted to provide forecast from medium range up to several months. Below the ZAMG analysis and nowcasting tool and the available NWP models are briefly introduced.

INCA analysis and nowcasting tool

The analysis and nowcasting system INCA (Haiden et al., 2011) algorithmically combines station observations, NWP model output and remote sensing data (radar, satellite) in order to provide meteorological analysis and nowcasting fields at high temporal (5 min) and spatial (1 km) resolution. INCA is used to calculate analyses and forecasts of a variety of parameters. The INCA analysis and nowcasting system is being developed primarily as a means of providing improved numerical forecast products in the nowcasting range (up to +4 h) and very short range (up to about +12 h) even though it adds value to NWP forecasts up to +48 h through the effects of downscaling and bias correction. INCA algorithmically combines station observations and remote sensing data (radar, satellite) in order to provide meteorological analysis and nowcasting fields at high temporal (5min – 1h, depending on parameter) and spatial (1 km) resolution.

Data bases
NWP background

For the three-dimensional INCA analyses of temperature, humidity and wind, NWP forecast fields provide the first guess on which corrections based on observations are superimposed. Beginning with 1st of March 2011 a new operational ALADIN configuration named ALARO was set to operations at ZAMG, replacing the old 9.6km version ALADIN-AUSTRIA. The new 4.8km version is coupled to the IFS model and uses the ALARO physics package. However, the INCA analysis and nowcasting methods do not depend critically on the horizontal resolution of the NWP fields and could as well be based on other NWP models.

Surface observations

One crucial data source for the INCA system is the input from surface stations. ZAMG operates a network of approximately 260 automated stations (TAWES) across the country which provides data in high temporal resolution. In addition, a high number of data from other providers such as hydrological services, avalanche warning services etc. are used.

Radar data

The Austrian radar network is operated by the civil aviation administration (Austrocontrol). It consists of five radar stations and ZAMG operationally obtains 2-d radar data synthesized from these five locations, containing column maximum values in 14 intensity categories, at a time resolution of 5 minutes. Ground clutter has already been removed from the data.

Satellite data

The Meteosat 2nd Generation (MSG) satellite products used in INCA are 'Cloud Type' which consists of 17 categories, and the VIS image. Cloud type differentiates between three cloud levels (low, medium, high) as well as different degrees of opaqueness. It also diagnoses whether clouds are more likely convective or stratiform in character. The VIS image is used to downscale the infrared-based (and thus coarser resolution) cloud types during the day.

Elevation data

The 1-km topography used in INCA was obtained through bilinear interpolation from the global 30" elevation dataset provided by the US Geological Survey. The resolution of 30" of the original dataset corresponds to ~930 m in latitudinal, and ~630 m (at 48°N) in longitudinal direction.

INCA and NWP output fields used for ADA (ARIS)

The ADA project partners have been provided with INCA analyses and NWP forecasts for drought specific applications (Tab. 2.2).

Table 2.2. Summary of the INCA analyses fields

Parameter	From year	**Forecast (d)**	**Resolution**
Minimum temperature (24 h) [°C d^{-1}]	2003	3 bzw. 10	1 km
Maximum temperature (24 h) [°C d^{-1}]	2003	3 bzw. 10	1 km
Mean temperature (24 h) [°C d^{-1}]	2003	3 bzw. 10	1 km
Daily mean temperature (12 h) [°C d^{-1}]	2003	3 bzw. 10	1 km
Global radiation [MJ m^{-2} d^{-1}]	2003	3 bzw. 10	1 km
Relative Humidity [% d^{-1}]	2003	3 bzw. 10	1 km
Wind [m s^{-1} d^{-1}]	2003	3 bzw. 10	1 km
Precipitation [mm d^{-1}]	2003	3 bzw. 10	1 km

2.3.2.2. Soil data and other spatial data inputs

The underlying soil data, especially crop available water storage capacity of the soil from 0-1m soil depth were derived from the Austrian electronic soil data bank (https://bfw.ac.at/rz/bfwcms2.web?dok=7066) for a grid size of 500x500m from soil texture information using transfer functions. The crop available soil water storage capacity and field capacity of the relevant soil layers (0-40cm and 40-100cm) are crucial for calculating actual and crop available soil water content and related crop drought stress status according to the applied algorithms (see Allen et al., 1998).

Summary of all spatial data bases used as input in the monitoring system are listed as follows:

- Digital elevation model [m]: 1 layer
- Field capacity [Vol%]: 1 top layer (0,4 m), 1 sub layer (0,6 m)
- Available field cap. [Vol%]: 1 top layer (0,4 m), 1 sub layer (0,6 m)
- Agricultural land use types (CORINE 2012): Grassland, arable land (for areas of winter wheat, spring barley, spring maize, sugar beet), grapevine areas
- Daily meteorological data (INCA): Relative humidity [%], Wind [m/s], Temperature [°C], Precipitation [mm], Radiation [MJ/m^2 day]

2.3.2.3. Crop water balance and crop phenology model

As basis for the crop specific determination of crop water use and soil water depletion a phenology model, calculating the crop phenology related crop water use parameter K_c, was calibrated and implemented into the modeling system in context to the soil FAO water balance model (Allen et al., 1998). K_c is the crop coefficient defined for a given crop and growth stage for calculating actual crop evapotranspiration (=crop water use) from grass reference evapotranspiration and is usually determined experimentally (Fig. 2.10). Each agronomic crop has a set of specific crop coefficients which can be used to predict water use rates at different growth stages.

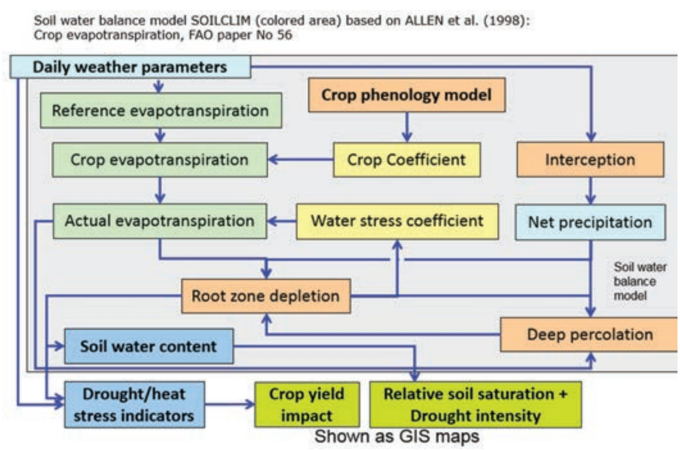


Figure 2.10. Crop-soil water balance calcucation scheme in ADA

Four main crop growth stages can be defined: initial, crop development, mid season, and late season (Fig. 2.10). For Austria the four crop growth stages as well as the Kc factor were defined for grassland, winter wheat, spring barley, spring maize and sugar beet. As experimental data were not available, calibrated crop growth models were used to determine the crop specific temperature sums required for reaching main development stages and related Kc factors.The DSSAT v4.0.2.0 model was used for maize, winter wheat and spring barley. The simulations were run from 1992-2012, weather station Groß-Enzersdorf, soil Chernozem, rain-fed, fertilization according ÖPUL guideline. On 1st March for winter wheat and spring barley as well as on 1st April for maize started the first stage A (Fig. 2.11). The Kc factor and temperature sum for sugar beet were simulated with the crop model Daisy.

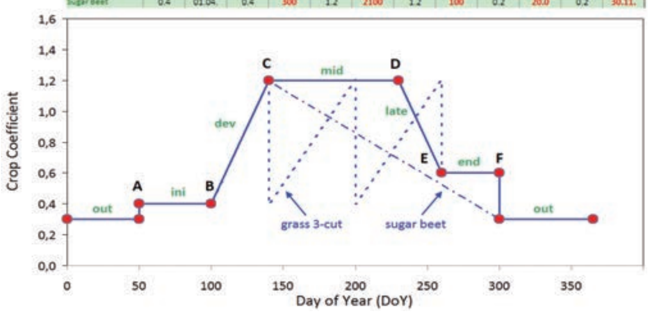
Crop Coefficient Model for ADA (Kc Factor)

Reference Evapotranspiration (ET0) for December, January and February is a constant value of **0.2 mm.**

Start of Growing Season (SGS): **First day of 5 consecutive days with daily mean temperatures above 5°C**
Start of Growing Season for Maize (SGS-M): **First day of 5 consecutive days with daily mean temperatures above 10°C**

Base temperature for calculation of degree day temperature sum (BT): **5 °C**
Base temperature for calculation of degree day temperature sum for Maize (BT-M): **8 °C**

Culture	Initial (Evaporation)			Crop Development	Mid-Season		Late Season		End of Growing			
	Entry of A		Entry of B		Entry of C		Entry of D		Entry of E		Entry of F	
	Kc	Time	Kc	Time (GDD)	Kc	Time (GDD)	Kc	Time (GDD)	Kc	Time	Kc	Time
Grassland (3-cut)	Will be done by LFZ Raumberg-Gumpenstein (according to Schaumberger, 2011)											
Winter Wheat	0.4	01.03.	0.4	SGS	1.2	592	1.2	953	0.5	+14 days	0.5	30.11.
Spring Barley	0.4	01.03.	0.4	SGS	1.2	816	1.2	767	0.5	+14 days	0.5	30.11.
Spring Maize	0.4	01.04.	0.4	SGS-M	1.2	572	1.2	2063	0.5	+14 days	0.5	30.11.
Sugar Beet	0.4	01.04.	0.4	300	1.2	2100	1.2	100	0.2	20.0	0.2	30.11.



Phenological model

(to be used for evapotranspiration calculation and stress indicators)

Figure 2.11. Crop growth stages and Kc factor for grassland, winter wheat, spring barley, maize and sugar beet as calibrated for Austrian conditions.

2.3.2.4. Drought indicators and Crop drought/heat stress and yield impact models

In ADA qualitative and quantitative measures for crop drought are calculated and presented. It can be summarized as:

A. Crop risk measures:

- General drought indicator (soil water content deviation in regard to the seasonal normal)
- Crop specific water stress factor (plant available soil water (AWC) content depletion - linear increasing stress beyond 30% AWC depletion)
- Heat stress factor (actual and accumulated)
  - number of days above maximum temperature limit
  - Duration above a critical Temperature

Table 2.3. Calibrated and statistically significant crop yield impact functions as implemented in the GIS model.

Crop	Daily heat indicator	Daily drought indicator	Daily drought/Heat indicator		Actually implemented yield depression functions		
Grassland 2nd cut		WSI = DR * 100.0 / TAW			YD = 87.53 + (-.0055 *Σ WSI)	Σ 1.5. - cut date	R^2=0.23
Winter Wheat	Σ HDH > 27	WSI = DR * 100.0 / TAW	TM > 26: CSI = WSI * (TM -25.0) TM < 26: CSI=WSI		YD = 6.64 + (-.000084 *Σ CSI)	Σ 1.3. – harvest	R^2=0.27
Spring barley	Σ HDH > 27	WSI = DR * 100.0 / TAW	WSI > 33 & TM>30: CSI= ((TM-29)*WSI)-33		YD = 5.11 + (-.0002 *Σ CSI)	Σ 1.3. – harvest	R^2=0.20
Maize		WSI = DR * 100.0 / TAW	WSI > 33 & TM>30: CSI= ((TM-29)*WSI)-33		YD = 10.99 + (-.0005 *Σ CSI)	Σ 1.5. - harvest	R^2=0.20
Sugar beet		WSI = DR * 100.0 / TAW	TM > 26: CSI = WSI * (TM - 25.0) TM < 26: CSI=WSI		YD = 89.22 + (-.0008 *Σ CSI)	Σ 1.5. - harvest	R^2=0.41

WSI = water stress indicator [%]
DR = root zone depletion [mm]
TAW = available soil water content at available field capacity [mm]
CSI = combined water and heat stress indicator [-]
TM = maximum daily temperature [°C]
YD = Yield depression relative to not stressed conditions [%]
HDH: Heat Degree Hours [°C]

- Combined heat stress x crop specific drought stress factor (way of combination of ad 1+2; i.e. reduction of heat stress impact above 70% AWC)

B. Crop vulnerability measures

- Crop specific heat and drought stress response at different phenological states expressed by yield depletion from normal.

Calibration and implementation of quantitative crop drought and heat stress parameters:

Based on established crop yield database for the major crops in Austria such as spring barley, maize, winter wheat and sugar beet, drought and heat stress impact analysis was carried out using the predefined indicators as shown in Tab. 2.3.

It shows the best performing indicators which were used for implementation in the ADA GIS system to calculate drought and heat stress related crop yield depletion.

2.3.2.5. System software ARIS of the operational monitoring system

The generation of ARIS (Agricultural Risk Information system) required several different working steps including the coding. The development was accompanied by additional tasks such as the preparation of meteorological, elevation, soil land use input data, the development and coding of a FTP download tool and of a web page prototype to visualise the results.

The first major working step of ARIS programming was the development and coding of adequate I/O interfaces to allow high performance data access and export. Based on the excellent performance and the relative small size of netCDF data files, the netCDF file format was chosen as main format for the creation, access, and sharing of the data.

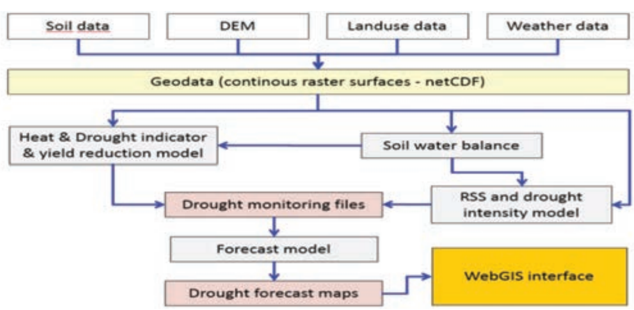
Due to the existence of the already developed submodels (SpatialGRAM and SOILCLIM) and their programmatic implementations, significant time was spent in a second major working step to analyse the methodologies of the two models and to select suitable algorithms for the new software. Appropriate algorithms were, for the most part, transferred unaltered and to a small part adapted to the project specifications. Furthermore new project specific methodologies and algorithms were also developed and implemented.

In the next step a new extensive program logic was coded including the existing and newly developed algorithms. All program features have been implemented as static or instanceable classes in accordance with the object-oriented programming paradigm. All classes with their class methods and the number and types of class variables and, last but not least, the program structure itself have been optimized with regard to a balanced ratio of computer memory consumption and processing speed. Several testing classes have been included to check the program's classes for functionality and correctness. Furthermore various methods have been implemented to export intermediate and final results of crucial calculation steps in ASCII text file format for evaluation and graphical visualisation purposes.

Besides ARIS, a separate application has been developed and coded to allow the download of all necessary meteorological monitoring and forecast files (1km gridded INCA data) from a download server of the Austrian Central Institute for Meteorology and Geodynamics ZAMG (Zentralanstalt für Meteorologie und Geodynamik). The meteorological files use the netCDF file format, are created on a daily basis and can be downloaded at any time. And last but not least a web page prototype was written to allow the illustration of the computation results. The web page is based on the open source platform MapServer (Univ. of Minnesota, USA), which allows the building of spatially enabled internet applications.

All components of ARIS are located on a Windows server. ARIS and the FTP download tool are triggered and controlled by the Windows task scheduler. The web architecture is depicted in Fig. 2.12.

Figure 2.12. ADA and ARIS system architecture.



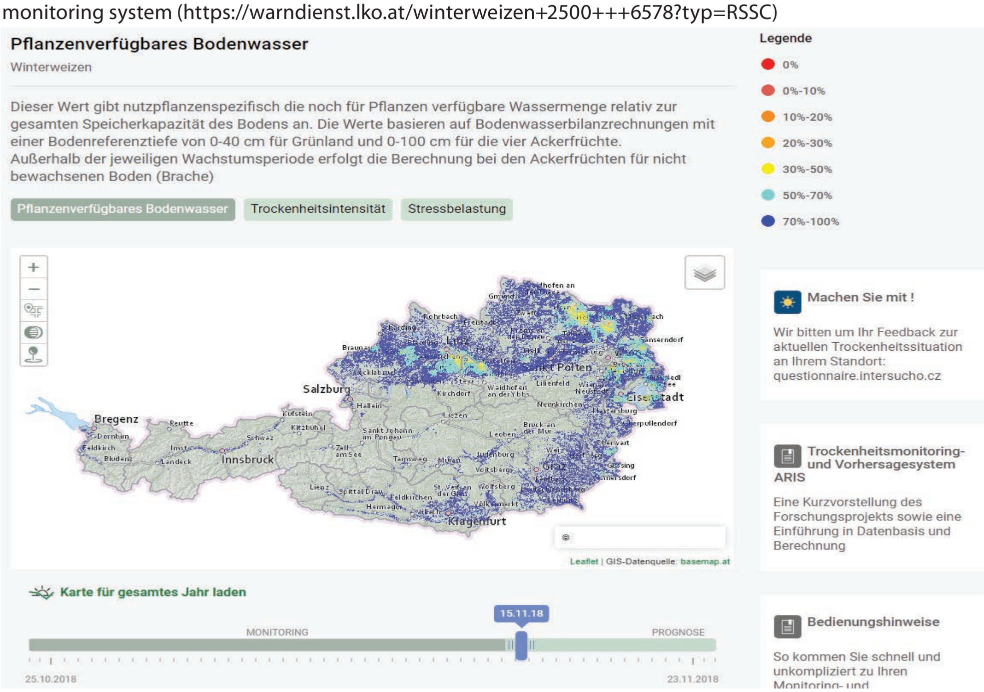
2.3.2.6. Summary of important system characterizations:

- All input/output data using the **netCDF** file format:
  -Data format for reading/writing large scientific data files developed by American company Unidata
  -Self describing (reducing the incidence of errors)
  -High-performance data format
  -Single and multidimensional grids (continuous surfaces)
- **Spatial resolution:**
  - DEM, Meteorological input data: 1000 m
  - Soil and landuse input data: 500 m
  - Output data (ET0: 1000 m, all other data: 500 m)
  - Resolution is increased using simple split algorithm
- **File Coverage:** Complete territory of Austria

2.3.2.7. Web portal of the monitoring system

The results of the Agro Drought Austria Monitoring and Forecasting System ADA (and ARIS) are maps showing the relative soil saturation, drought intensity and crop yield reduction situation over the Austrian territory in a grid resolution of 500 meters for rooting zone layers of 0-40 cm (grassland) and 0-100 cm (winter wheat, spring barley, maize and sugar beet). The maps are visualised in the web page (Fig. 2.13).

Figure 2.13. Crop available soil water content for winter wheat as presented in the operational drought monitoring system (https://warndienst.lko.at/winterweizen+2500+++6578?typ=RSSC)



2.4. Drought tolerance - example of sugar beet

2.4.1. History and distribution of sugar beet

First information about root beet growing dated from ancient times. In Byzantium, the beet was regarded as a "trade item" in the 8th century, which suggests that the root beet originates from the Middle East. To the north of the Black Sea, beet cultivation was widespread in the 10th century, while in Western Europe the cultivation of this culture began after the end of the Crusades (XII and XIII centuries), first in the area of Northern Italy and in the roll of the river the Rhine. Heinisch was collected information that the history of sugar beet as a cultural plant, based on detailed research by a large number of researchers, found that the first traces of the cultivation of beet originated in the 1000 years before our era. It was proven that white and red beets were grown at that time in Sicily. According to the same author, the beet was mentioned in the Middle Ages for the first time in 812 in the regulation of Charles the Great. According to Helm (1957), the beet as a root plant with a thickening root, is known only in the fifteenth century.

Sugar beet, as a source of sugar, was first registered in 1750. Since 1880, the sugar beet has replaced the sugar cane, which had been the main source of sugar in continental Europe. The current trend of sugar production is again in favor of sugar cane, so the sugar beet in the 1990s participated with 30-40% in the world's total sugar production. In the first years of this century this percentage was 16, from about 234 million tons to about 5, 9 million hectares. About 85% of the world's total production is produced in Europe. In addition to the European Union, the largest producers in the world are Brazil and India.

In Serbia the beginnings of sugar beet growing date from the end of the XIX century. Today sugar beet is widespread on about 52 000 ha, with an average yield of about 34 t/ha, which makes production of 1.7 million tons. Of the total sugar beet production in Serbia, 95% is produced in Vojvodina.

The drought is big problem in many countries (Australia, USA, China, Mediterranean countries). It could be solved by new methods of irrigation, so-called method of irrigation deficit, when plants are irrigated with a smaller amount of water. These methods include regulated deficit irrigation (RDI) and partial root drying (PRD). RDI is an irrigation technique where the root system of plants is irrigated by a smaller amount of water, compared to possible evapotranspiration. In this way, plants are exposed to moderate stress, but they are not significantly reducing the yield. PRD is an irrigation technique that developed after RDI and implies irrigation of only a part of the root system while the other part dries to the pre-planned level. Then an inversion is performed, the irrigated half is dried and the dried half is irrigated. The application of this technique is simple. Theoretical basis for these methods is in the induction of adaptive plant reactions to drought.

A particular problem for Serbia is that the lack of water in the soil, which is especially pronounced in the summer months, is not only evident in dry, but also in moderately wet years. The soil moisture deficit is 100-200 mm, rarely 300 mm per year. The current state of irrigation in Serbia is such that it is intensively irrigated by less than 1% of agricultural areas that are suitable for irrigation. The current state of research at the national level of drought in Serbia, as well as in many countries, has become an increasing problem in the last decades. Climate forecasts indicate that this negative drought trend will continue. The concept of economical use of existing water resources for the agricultural production also implies needs for increasing efficiency in the use of water by crops. This can be achieved if the water needs of cultivated plants and their resistance to drought are well known. In Serbia, in scientific projects, there are insufficiently studied mechanisms of influence of efficiency of water utilization which are important for the drought tolerance of plants, although it could help in the selection of resistant genotypes for the purpose of planting plants in drought-affected areas. Selection of tolerance to drought is complexity of plant resistance reactions and it is not sufficiently represented, and is especially relevant for mature crops (corn, soybean, sugar beet and sunflower). The institutes from the UK, Denmark and Portugal were the first who begin with the practical application of knowledge in the field of physiology of stress for overcoming or reducing the effects of drought and start with selection of tolerant genotypes.

An overview of the world researches indicates how complex is the problem of drought, and the need to approach this problem multidisciplinary in the view of other developed countries. Drought is an abiotic factor that greatly endangers the yield of sugar beets and in our agroecological conditions. The physiological, biochemical and molecular mechanisms that are activated in plants under water shortages conditions is therefore the subject of numerous researches. Defining the most relevant criteria for assessing tolerance for water deficiency is very important for breeding in order to create genotypes that better cope with this abiotic stress. It is believed that the application of molecular methods, together with classical physiological and anatomical research, can give the best results. The molecular methods, at the current level of knowledge about the functioning of the sugar beet genome, are the most direct approach in the testing the usability of certain published sequences associated with the reaction of plants to osmotic stress (gene candidate) for the purpose of breeding.

2.4.2. Water amount and distribution of water necessary for successful development of sugar beet

Optimal amount of precipitation for successful production of sugar beet is 600 mm per year. Furthermore, during the winter period, sugar beet requires around 230 mm of precipitate and during the period of vegetation, from April to October, approximately 370 mm. But, based on perennial average yield data, sugar beet production may achieve high outcome even in presence of lower (500 mm per year) or higher (1000 mm per year) amount of rain. Water requirement of plant, during the period of vegetation, depends on precipitation. The water loss due to evaporation is most intensive from June to August when the temperatures are often very high and the air is dry. The average potential evapotranspiration (ET) for period of thirty years in case of sugar beet is 576 mm, but it may vary between 528 and 625 mm due to weather conditions. Approximately 10-20% of total water requirement of sugar beet is fulfilled from the soil water reserves and the rest is obtained by precipitation and irrigation. The amount of water lost by transpiration is 392 mm in average, and it varies from 198 mm during dry years to 542 mm during rainy years. The average precipitation during vegetation from April to September is 359 mm and it varies from 138 mm to 521 mm in certain years.

Having in mind above mentioned facts, amount and distribution of precipitation, in combination with the light and amount of heat mostly determine quality and yield of sugar beet. On the territory of Serbia, it is common that the lack of soil water, typical for summer months, sometimes occurs during moderately rained years. Lack of soil moisture outcomes 100-200 mm per year, but rarely exceeds 300 mm per year. Currently, less than 1% of irrigation-suitable agricultural land in Serbia is intensively irrigated.

Climate of Serbia is continental or moderate-continental. The most important sugar beet production area is Vojvodina region situated in the north of the country. Climate of Vojvodina is moderated continental, determined by presence of Alps on western border of Panonian basin, Carpathian Mountains, the Dinarides and the Balkan mountains. Precipitation regime is continental, typical for Danube region, with precipitation maximum in summer (June) and minimum in winter. According to the Köppen classification, for the period 1961-1990 dominant climate type in Vojvodina is *Cfwbx*" [*C* = mild temperate climate; *f* = significant precipitation during all seasons; *w* = dry winters; *b* = warmest month averaging below 22 °C (but with at least 4 months averaging above 10 °C) and *x*" = second precipitation maximum occurs in autumn].

Brief analysis of current and expected precipitation distribution during winter, spring and sugar beet growing season in Vojvodina is made using data for two meteorological stations located in southern and northwestern part of the Vojvodina region, Novi Sad (Rimski Šančevi) and Sombor, respectively. Climatological data for 1971-2000 reference climatological periods derive from the database of the Republic Hydrometeorological Service of Serbia (RHMSS). Future climate conditions were obtained from the Eta Belgrade University (EBU)-Princeton Ocean Model (POM) model for the A1B scenario over the 2001–2030 and A2 for 2071–2100 integration periods. Obtained results lead to expected shift in climate types from *Cfwbx"*to *Cfwax"* in the prevailing part of the country indicating temperature of the warmest month above 22 °C (letter *a* in the Köppen formula).

Overview of average precipitation for selected past climatological period, indicates that during winter time of 1971-2000 reference period, amount of precipitation is twice less than optimum ones while growing period of precipitation was slightly below optimal values.

According to climate model simulations for 2001-2030 integration periods, expected average annual precipitation during first decades of XX century, at selected locations, will not vary significantly in relation to the 1971-2000 precipitation records (Tab. 2.4). Inspection of precipitation amounts for 2001-2014 period (Tab. 2.5) witnesses in favor to this expectation, with 699.8 mm in Novi Sad and 668.0 mm in Sombor in comparison with expected 2001-2030 average (Tab. 2.4).

However, it is important to notice significant variability of precipitation in this period which is in accordance with climate simulations for 2001-2030.

Climatol. period	Annual	Winter (DJF)		Spring (MAM)		Growing season	
	Precip. (mm)	Precip. (mm)	Var. coeff. (%)	Precip. (mm)	Var. coeff. (%)	Precip. (mm)	Var. coeff. (%)
	Novi Sad (Rimski Šančevi)						
1971-2000	604.1	108.1	46.2	146.6	33.3	359.2	28.8
2001-2030	641.8	131.3	56.1	159.7	34.7	369.2	26.1
2071-2100	560.5	131.0	54.5	147.4	37.0	282.2	32.0
	Sombor						
1971-2000	580.3	107.6	41.9	133.3	29.6	339.4	22.7
2001-2030	629.4	127.3	56.7	144.6	37.2	356.5	29.0
2071-2100	565.8	127.2	53.6	148.1	41.3	277.8	31.9

Table 2.4. Past and future climate precipitation data for Novi Sad and Sombor locations in Serbia

Table 2.5. Annual amount of precipitation for 2001-2014 in Novi Sad (Rimski Sancevi) and Sombor locations.

Year	Novi Sad (Rimski Šančevi)	Sombor
2000	252	231
2001	929	749
2002	412	448
2003	491	434
2004	797	816
2005	726	753
2006	640	585
2007	754	683
2008	539	598
2009	617	615
2010	1035	994
2011	382	401
2012	480	446
2013	723	692
2014	989	932
Average	679.8	653.3

With regard to winter and spring precipitations, for all integration periods, climate model simulates slightly higher average precipitation in comparison to reference climatology. Less optimistic is expectation that growing period precipitation supposed to decrease towards end of the century, with particularly vulnerable summer period and increasing variability.

2.4.3. Effect of drought on sugar beet production

Lack of water during vegetation is frequent and significant issue in agricultural production (Figure 1.). Possible solution to this problem is selection of genotypes which do not show decreased yield under economically acceptable level, in the presence of water shortage. Great challenge in the process of genotype selection is to choose the convenient plant idiotype for the present agro-climatic conditions. Water deficiency has complex impact on plant physiology. Water deficiency leads to loss of turgor pressure and stomatal closure in plants. Photosynthesis is also highly dependable on plant water supply. Many studies showed that disruption of water flow causes decrease in water content in assimilation tissue which leads to photosynthetic depression. Based on this, soil moisture, as well as relative air humidity, determines photosynthetic intensity. A decrease in chloroplast size, an increase in stomatal density and disruption of tilacoid membrane structure, were reported as consequences of water deficit. Besides decrease in tissue water content, water shortage may cause synthesis of specific compounds in the roots, during the early growth phase. According to this, roots are very significant sensors of soil changes (not only in terms of water, but also texture changes), which alert the aboveground tissues by "chemical drought signals" which are transported to leaves. These signals mostly refer to plant hormones such as abscisic acid (ABA).

Figure 2.14. Sugar beet exposed to water deficit

2.4.4. Tolerance of sugar beet to lack of water

Plant metabolism could adapt on stress conditions, it is species specific and was subject of numerous studies (Fig. 2.15). Plants more tolerant to drought have longer root system with bigger absorptive area, better developed photosynthetic parenhyma, thicker cuticle, smaller leaf area and number of stomata per leaf area and higher density of conductive elements. They also possess highly expandable protoplasm, higher content of bound water and osmolytes, enhanced accumulation of ABA, free proline and alanine. The following indicators point out to higher phenotypic tolerance of sugar beet to water shortage: more shiny leaves, higher turgor pressure of petiole and more sensitive leaves to expansion. Even though there is genotypic variability with respect to response to drought in sugar beet structural and morphological mechanisms still remain unclear.

During early stages of growth and development stress occurrence may adversely affect sugar beet root growth which may result in yield loss by 46%. In addition, later stress occurrence may cause decreased leaf area and also number of leaves and by that, the efficiency in light usage becomes decreased. Lack of water significantly increases concentrations of potassium and sodium which disturb sugar extraction from roots. Plant response to water stress can partially be explained by disorders in mineral nutrition. Water shortage actually may retard or even stop ion assimilation which results in

Figure 2.15. Tolerance of different sugar beet genotypes exposed to the same period of water deficiency

perturbation in ion ratios in specific tissues. This trend is manifested through ion deficiency symptoms in plants. The adverse effect of water stress in later phenophases is less pronounced, since plants already developed root system and canopy which completely covers the soil. Well-developed root system increases efficiency in water extraction and usage, which results in higher tolerance to water deficiency. However, first signs of water stress are usually seen on leaves. Minor drop in leaf water potential may cause significant decrease of total leaf area and the low water potential enhances emergence of new leaves and accelerates senescence of old leaves. Drought stress results in stomatal closure, limits the transpiration which increases leaf temperature. Both lower stomatal density and heat stress decrease photosynthetic outcome. Sugar beet leaves have higher number of smaller stomata on their abaxial side. Higher density and smaller size of stomata is a form of adaptation to drought, because it allows plants to be more efficient in regulation of water transport and transpiration. Varieties more efficient in tolerating lack of water are proven to have decreased stomatal density (70-150 stomata/mm^2). During drought, when negative turgor pressure in guard cells generates, small epidermal cells with tightened cell walls increase plant resistance towards water stress. Response of sugar beet genotypes to drought may also be affected by percentage of adaxial and abaxial epidermis and palisade tissue thickness.

Plants could osmotically adapt to drought, too. Exposure to water deficiency results in accumulation of osmolytes such as betaine, proline and fructans. These substances often accumulate in form of compatible solutes in plants (compounds which do not take part in chemical reactions in plants, but affect cell water potential), which generate expression of genes encoding relevant enzymes. Osmolyte production, as well as change in osmotic pressure, may increase sugar beet tolerance to abiotic stress. Proline and glycine betaine help the preservation of cell, which makes them suitable for further investigation with purpose of increase stress tolerance of many species including sugar beet. They are involved in maintenance of cell turgor and osmotic balance but also in protection of cell structure from stress. However, it still remains unclear whether the plants, which accumulate osmolytes, better tolerate lack of water or not.

Free proline is important metabolite which accumulates in sugar beet exposed to drought (Fig. 2.16). Changes in the concentration of free proline in plant tissues is an indicator of stresses such as temperature, environmental pollution, and misbalanced nutrition. The same factors may affect glucose accumulation and yield. In some cases stress conditions may increase sugar beet root quality and potential of recovery if plants were not highly damaged by water deficiency.

Fertilization with higher concentration of nitrogen also increases proline content, may increases leaf area index (LAI) and drought stress impact. Positive and significant correlation among proline and glucose content in sugar beet root indicates the relationship between the response to stress, carbohydrates and proline and glucose accumulation ratio. This is supported by the effect of treatment with di-1-p-mentene (anti-transpirant) and DMDP (2, 5-dihydroxymetil-3, 4-dihydroxypyrolidine, glycosidase inhibitor), which decreased proline content in roots of irrigated sugar beet. Presence of compounds such as proline and glucose adversely affect sugar crystallization and lead to the formation of colored components, thus reducing industrial quality of beet roots.

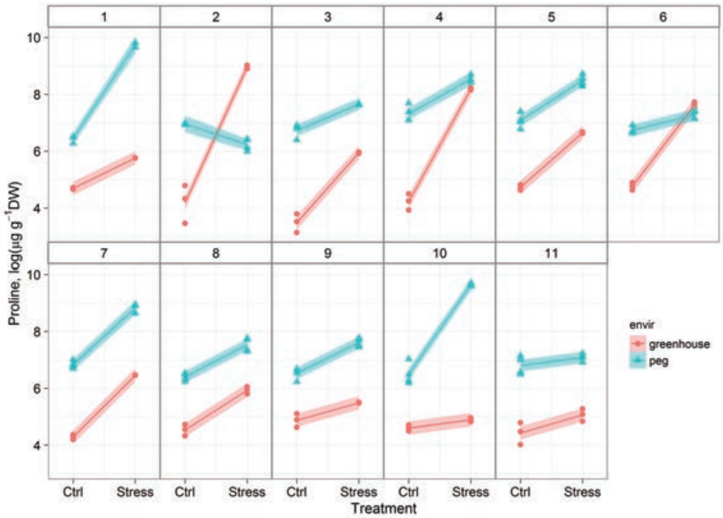


Figure 2.16. Free proline accumulation in 11 genotypes of sugar beet exposed to water stress in different environment (experiment in greenhouse and in tissue culture)

Free proline accumulated in sugar beet root, as a nitrogen compound, reduces the quality of roots. Both, the stress and an excess of nitrogen lead to the mobilization of accumulated carbohydrates which are the source of energy essential for adaptation to the stress conditions. Moreover, chemicals containing nitrogen (e.g. proline), reduce the yield of sucrose, and the quality of the roots. The importance of the accumulation of proline in osmotic adjustment is still debatable and varies from species to species. The highest proline accumulation was observed at the end of beet root growth. Correlation between drought and proline content suggests, however, that alteration in proline concentration is useful stress indicator in sugar beet. Proline may act as a signal molecule which alters mitochondrial function, affects cell division and gene expression. This role of proline may be very significant for plant recovery when favorable conditions are regained.

2.4.5. Prospectives to increase tolerance to water deficiency by biotechnology

Need for sustainable food production directed research programs towards improving traits of crops despite the size and complexity of their genome. Plant biotechnology is a process in which the use of molecular and cytological techniques help to increase the productivity of the plants, to improve the quality of plant products, to prevent the damage caused under the influence of various biotic and abiotic stresses. Plant breeding reliving on the employment of molecular markers (MAS - Marker Assisted Selection) is one of promising techniques to improve crop reselience. A prerequisite for the success of MAS is defining the genes which regulate traits of interest and to test relationships between potential markers and those traits. Only when this link is defined, i.e. when the marker is physically located in the vicinity of or even within the gene of interest, it is possible to use it efficiently in breeding.

Development of breeding programs aimed to increase drought tolerance of sugar beet is further complicated by the fact that several types of abiotic stresses often occur at the same time during the growing season. This complex problem could be solved by approach which involves a manipulation of a group of genes for tolerance to drought.

In an era of fast progress in the identification and characterization of complete segments of plant genome, proteins, transcripts, metabolites, as well as their interactions in a biological system, new discoveries will lead to better understanding and possibly to manipulation of physiological responses to water deficit. Evaluation of the relative contribution of genes conferring tolerance to the dehydration and elimination of those which do not affect the tolerance to stress is a major challenge.

Even though the yield is the basic goal of the breeders, it is very difficult to accurately predict the possibility of water utilization and identify candidate genes for further cloning. Several studies have identified QTLs (quantitative trait loci) associated with a specific component of the response to drought. Although the development of molecular markers and genome sequencing should expedite positional cloning genome areas associated with individual QTLs are still very large and usually not suitable for testing in the breeding program. With the fast development of genomic technology and the suitable statistical methods, there is an increased interest in the use of mapping strategies for the identification of genes encoding quantitative traits which have agricultural or evolutionary significance. Another major challenge is how to apply knowledge to improve crop tolerance to stress conditions. There is a problem between high yield and tolerance to stress since very often genotypes with higher stress tolerance have lower yield under optimal conditions.

On the cellular level plant adaptation to stress includes regulation of the beginning of protein synthesis (e.g., H+ pumps and Na+ / H+ antiporter), an increase in antioxidant level, transient increase of the concentrations of ABA, the reduction of the energy consumption ways, as well as accumulation of the solution, and protective protein. All of these changes at the cellular level are of great importance for the maintenance of homeostasis after ion imbalance caused by abiotic stress. The deficit of water causes the synthesis and accumulation of ABA in plant cells and the genes corresponding to this has been defined. Most of these genes contain conserved cis-activating promoter elements, called Abre (ABA-responsive element). Great progress to clarify the response of plants to abiotic stress has been made in the last decade.

In order to achieve a combination of high yield and tolerance to stress in one variety, it is necessary to establish a connection of development of individual characteristics and mutual reactions which can be achieved only through cooperation among molecular biologists, physiologists and breeders. It is necessary to assess relationship between different morphological, anatomical, physiological and biochemical traits of sugar beet tissues in different phases of their growth and development during different periods of water shortage, in order to categorize genotypes with respect to their tolerance to drought which was in the focus of our previous and present study.

2.5. Impact of excessive salts and mechanisms of crop adaptations

2.5.1. Summary

In some soil types, the salt content of the soil solution can be significantly increased. For the majority of cultivated plants, soils with concentration of salts in the soil solution between 0.001 and 0.01% are convenient for plant production. Salt concentrations above 0.01% are already unfavorable for most cultivated plants. Plants that are adapted to a higher salt concentration are called halophytes, and those that are sensitive to salts are called glycophytes. Among the cultivated plants there are no real halophytes, but nevertheless, cultivated plants may differ greatly with respect to their sensitivity to excess salts. Of cultivated plants, the most tolerant are: sugar and fodder beet and cotton. The tolerance of individual plants to NaCl is based on different mechanisms, whereby three basic modes of adjustment can be distinguished.

1. In some plants (like barley) Na^+ is passively taken up and actively transported out of the cell. In the cells of such plants concentration of Na^+ and Cl^- is low.
2. Some plants dilute the concentration of salts in their cells. They are similar to xerophytes, i.e. distinctly succulent. The succulent features of halophytes is the result of the physiological impact of salts. A prototype of this group is *Sueda maritima*.
3. A group of plants tolerant to salts is characterized by active excretion of salts over specific salt glands (e.g. *Atriplex* and others).

Tolerance of plants towards high concentrations of salts can also be based on compartimentation of ions in the cell, for example, by their accumulation in the vacuole, or based on the existence of a barrier which prevents the uptake of ions in the roots or their transport to shoots.

Halophytes can be obligatory and optional. The characteristic feature of the halophyte is high content of mineral matter, which helps to maintain the concentration of cell solution higher than the soil solution, which is essential for the uptake of water by the root system. In some halophytes the content of mineral matter in dry matter can be up to 50%. Therefore, halophytes are characterized by very high osmotic pressure. In the presence of excess salts, productivity of plants is greatly reduced, especially in species that are salt-sensitive. Even if the rate of photosynthesis is not significantly altered, the overall plant productivity may be significantly changed because total leaf area is usually significantly reduced. In conditions of high concentration of salts there are disturbances in metabolism of nitrogen compounds. Accumulation of free amino acids, amides and diamine (putrescine and cadaverine), especially in the root, typically accumulate.

In addition to concentration, the ionic composition of the salts is also important, since the action of some ions on physiological processes of plants is specific. The tolerance of plants to salts has outstanding practical relevance since in many regions of the world agricultural production is limited by high concentration of salt in the soil solution. It is believed that more than 25% of the soils and 95% of the water on Earth is salty.

Faster or a slower increase of salt concentration in the soils in greenhouse production may occur due to unprofessional irrigation, excessive application of mineral fertilizers, etc. It is crucial to take care of the quality of irrigation water applied to soils on which the concentration of salts has already been increased. More recently, efforts have been made to produce crop genotypes, through breeding, which display better tolerance towards higher salt concentrations, that could be grown on soils with increased concentration of salts or which would even tolerate sea water irrigation.

2.5.2. General impact of excessive salts in soil solution

Stress caused by increased salt concentrations affects plant metabolism and the final outcome of plant production in many ways. The excess of salts has an osmotic effect, which means that it reduces the amount of water which plants can take up by their root system. Some ions can be toxic to some processes in plants. Increased salt concentrations can lead to disorders in the mineral nutrition of plants, to plant hormone imbalances, and to the formation of reactive compounds such as different types of oxygen but also other free radicals that may damage cell membranes. Plant cells, tissues, organs, individual plants but also the whole ecosystems can have or develop mechanisms that protect them against the adverse effects of elevated salt concentrations.

In agricultural practice, it is not always possible to provide enough water for irrigation of good quality. Strongly mineralized waters, as well as processed waste water, are often used for irrigation. In this way, useful or harmful salts, but also various other compounds can be introduced into the soil, which depends on the quality of the water. Very often in the irrigation water there is too high concentration of ions. The use of such waters, especially during longer period, may significantly affect soil quality and plant production.

The excess of salts in arable land is a problem that is becoming increasingly common in many areas where irrigation is a regular agro-technical measure, as well as in arid and semi-arid regions of the world where atmospheric precipitation is not sufficient to wash salts from the root zone system. When irrigation water is of inadequate quality, the appearance of chlorosis between the leaf nerves, tissue necrosis of the leaves, and the absence of flowering is often observed on plants. The vegetation is usually shortened and biomass production reduced. The length of the period during which plants were exposed to excess salts is also very important for their overall impact on plant growth, physiological processes and biomass production. The type of salts which are building up increased soil salinity is also very important.

According to the FAO (1997), saline soil is the one whose electrical conductivity (EC) is 4 dS m^{-1} and above, while soil with EC exceeding 15 dS m^{-1} is considered to be very saline. Cations which are most commonly associated with saline soils are Na+, Ca^{2+} and Mg^{2+}, while anions that accompany them are Cl^-, SO_4^{2-} and HCO_3^-. However, the most important are considered to be ions of Na^+ and Cl^- since they are both toxic to plants. Sulphates that otherwise participate in the metabolic processes of plants as an integral part of the amino acids which build up proteins (and enzymes) may also interfere with plant metabolism. They are usually more toxic than chlorides. However, for some woody types of fruits, such as grape vines and citrus fruits, as well as many species of trees, Cl^- is more toxic than SO_4^{2-} and causes characteristic fractures on the leaves.

Type of water	Total dissolved salts (ppm)	EC ($dS\ m^{-1}$)	Plant species	Threshold EC ($dS\ m^{-1}$)	Degree of tolerance*
Sweet water	< 500	< 0.6	all		
A little brackish	500 – 1000	0.6 – 1.5	Beans	1.0	S
			Carrot	1.0	S
			Onion	1.0	S
			Strawberry	1.0	S
			Eggplant	1.1	MS
			Melon	1.2	MS
			Radish	1.2	MS
			Lettuce	1.3	MS
			Pepper	1.5	MS
Brackish	1000 – 2000	1.5 – 3.0	Maize	1.7	MS
			Potato	1.7	MS
			Garlic	1.7	MS
			Potato	1.7	MS
			Alfalfa	1.7	MS
			Cabbage	1.8	MS
			Celery	1.8	MS
			Spinach	2.0	MS
			Squash	2.5	MS
			Tomato	2.5	MS
			Rice	3.0	
Moderately saline	2000 - 5000	3.0 – 8.0	Peas	3.4	MS
			Red beet	4.0	MT
			Soybeans	5.0	MT
			Wheat	6.0	MT
			Sorghum	6.8	T
			Sugar beet	7.0	T
			Barley	7.7	T
Saline	5000 - 10000	8.0 – 15.0			
Very saline	10000 - 35000	15.0 – 45.0			

Table 2.6. Classification of water with respect to the total concentration of salts and tolerance to salts of some herbaceous plants (after Hillel, 2000 and Maas, 1990)

* Degree of tolerance: sensitive (S), moderately sensitive (MS), moderately tolerant (MT), tolerant (T)

2.5.3. The influence of excessive salts on plant growth

The response of plants to the presence of increased amounts of salt in the soil solution is at the first place the retardation in growth. Together with the composition of soil solution, the other environmental factors, such as relative humidity, temperature, light, and air pollution, have a significant impact on the final effect of soil salinity. Salinity causes anatomical changes in the leaves of many plant species. For example, the epidermis and mesophilic leaves of the beans, cotton and *Attriplex* become thicker, the length of the palisade cells and the diameter of the spongy cells grow and the thickness and the palisade and spongy layer increase. The other plant species may have the opposite phenomena. For example, after treatment with NaCl leaves of the *Brugueira parviflora*, the thickness of the epidermis, mesophyll and intercellular spaces decreased. In leaves of spinach, exposed to salts during growth, intercellular spaces decreased, and in tomato density the stomata decreased in the presence of salts. The expansion of the vine leaves, expressed through changes in the index of the leaf surface in time, as well as the conductivity of the stomata, are more susceptible to salts than transpiration and photosynthesis.

Table 2.7. Effects which increased concentrations of salts have on tolerant species/genotypes are fundamentally identical to those induced by water shortage and depend on the length of exposure to salts (after Munns, 2002)

Time	**Effect of stress induced by water shortage** (Effect on the growth of plant tolerant to excess salts)	**Effect specific to the presence of salts** (Additional effects on growth of plants sensitive to excess salts)
Minutes	Fast slow of elongation of leaves and roots and then quick recovery	-
Hours	Continuous but slow elongation of leaves and roots	-
Days	Leaf growth reduced more than root growth; Slow emergence of new leaves	Damage visible on the oldest leaves
Weeks	Reduced final leaf size and / or number of lateral outgrowths	Dying of older leaves
Months	Altered flowering time, reduced amount of produced seeds	Younger leaves die, the plant may die before seed ripening

Accumulation of salts in the leaves causes premature aging, which reduces the provision of photosynthetic products to plant parts that grow fastest and thus the growth of the entire plant is reduced. In more sensitive genotypes, salts accumulates faster and cells are unable to sequestrate accumulated ions of salts in the vacuoles to the extent that can more tolerant genotypes. Therefore, leaves of more sensitive genotypes tend to die faster. Inhibition of leaf growth due to excessive salt concentration reduces the volume of new leaf tissue in which excess salt can accumulate and, therefore, in combination with continuous salt accumulation, this may lead to an increase in overall salt concentration in plant tissues.

It is often very difficult to distinguish and assess the relative impact of the osmotic effect and the specific toxicity of the individual ions on crop yield. In any case, loss of yield due to osmotic stress can be very significant even though the symptoms of leaf toxicity are not noticeable. Numerous researches have been and are conducted to find sources of tolerance to increased salt concentration in cultivated plants, in our agroecological conditions especially on wheat. There are remarkable differences in salt tolerance between plant species and genotypes as well as between measured parameters used to assess the degree of tolerance towards excess salts. The same applies to the ability to tolerate water shortages.

In the presence of excessive salts in the soil usually a greater reduction in the growth of the above-ground parts than of roots is observed, especially at high concentrations of NaCl, which probably means that the root has a better osmotic adjustment capability compared to shoots. To what extent Na^+ and Cl^- affect the growth of plants depends significantly on the plant species and to a lesser extent on the genotype. Salinity causes anatomical changes in the leaves of many plant species.

Ecosystems
Plants
	Effects of salinity
	• Global increase of salinity (global salinization)
	• Environment
	  • Plants
	  • Soil	

↓
Organs, cells
↓
Cell compartments
	Responses to salt stress
	• Osmotic effects
	  • Changes in turgor pressure
	  • Biosynthesis of osmolytes
	• Effects specific for particular ions
	  • Ion toxicity
	  • Disturbances in mineral nutrition
	• Oxidative stress
		• Signal transduction
		• $[Ca^{2+}]$ in cytosol

↓
Membranes
	Effects specific for particular ions
	• Exclusion of ions from metabolism
	• Ion accumulation
	  • Ion toxicity
	  • Ion compartimentation
	    - Apoplast
	    - Cytoplasm
	    - Vacuole
	  • Regulation of ion transport
	• Disturbances in mineral nutrition
	  • Inhibition of the uptake of ions
	  • Loss of selectivity K/Na, effects of Ca	

↓ **Molecules**	**Factors which affect tolerance towards excessive salts** • Genes • Proteins • Enzymes • Secondary messengers • Phytohormones • Antioxidants • Transporters located in membranes • Compartimentation of dissolved particles • Compatible osmolytes	

Figure 2.17. Mechanisms of tolerance of pants towards increased concentrations of salts and toxic effects of salts on them (after Pitman and Läuchli, 2002)

2.5.4. The influence of soil salinity on plant water regime

The main cause of the reduced growth of plants in the presence of salt can be the result of the effect of salts on the water regime of plants. Increasing the salt concentration in the soil increases the osmotic pressure of the soil solution and the plants cannot take up water easily as in the case of relatively non-saline soils. Soluble salts increase osmotic potential over and above the matrix potential that already exists in the soil and depends on its properties and dissolved substances. Therefore, concomitantly with an increase in salt concentration, i.e. with increase in the soil EC, water becomes less accessible to plants even if the soil contains significant amounts of water and looks damp. Osmotic pressure depends on the number of particles in the solution as well as on the temperature. The osmotic pressure (OP) of the extracted soil solution can be expressed through an empirically obtained form that reads: OP = 0.36 x EC (dS / m). At a pressure of about 1.44 bars, corresponding to an EC of 4 dS/m, plants begin to show signs of water stress caused by a physiological water shortage. Therefore, in the soil containing excessive salts, despite the fact that water can be physically present, it becomes inaccessible to plants, and this phenomenon is called physiological drought.

The first effects of excessive salts, especially when it comes to lower and moderate salt concentrations, can be attributed to the increase in the osmotic value of the soil solution. With the increase saturation of soil solution with salts, the uptake of water through the root system becomes more difficult and reduction of evapotranspiration and yield takes place. There are several reasons why evapotranspiration decreases with the increase in concentration of salts in the soil. Due to the increase in the osmotic value of the soil solution, the accessibility of water to the root system is reduced. Decrease in root growth leads to a reduction in the total root absorption surface for water and nutrients. At the same time, total leaf and therefore transpiration surface of plants declines. As one of the mechanisms by which plants protect their cells from the inadequate action of high salt concentration is dilution, then water retention in plant tissues increases, which further reduces transpiration. These factors reduce the efficiency of water utilization by plants and, as a result, reduce the growth of plants and yields. Vegetation is shortened, water regime disturbed and uptake and distribution of essential elements in both field and semi-controlled conditions impaired.

At very low water potential of the soil, the uptake of water and the maintenance of turgor pressure in the tissues becomes very difficult. Because of this, osmotic stress in a large number of plant species resembles a stress caused by a lack of water. The water potential of leaves well-supplied with water ranges from -0.2 to about -0.6 MPa, but leaves of plants in arid regions may have significantly lower values, from -0.2 to even -5 MPa in extreme conditions. Since the uptake of water is a spontaneous process, the water potential of the root cells must be less negative than the water potential of the soil solution so that the root can absorb water. If, due to the increased salt concentration, there is a small difference between the water potential of the soil solution and the root cells, the plants can osmotically adjust by accumulating in their cells the so-called osmolytes. By doing this, the plants maintain the water potential of their cells more negative in relation to the water potential of the soil solution and maintain the continuous absorption of water and water flow through their tissues.

Increase in the concentration of salt in the medium in which the root develops leads to the reduction of the osmotic potential of the leaves, which reflects on many processes in affected plants. Several authors have found that the aquatic and osmotic potential of the plants is becoming more negative with an increase in the concentration of salts in the soil solution, while the turgor pressure increases.

2.5.5. Accumulation of compatible osmolytes increases tolerance to osmotic stress

One of the ways in which plants can osmotically adapt to stress conditions is the accumulation of salt ions, if these salts are isolated in individual cellular compartments, thus preventing their involvement in cell metabolism. The ability to regulate salt concentration through compartimentation is a very important aspect of tolerance towards increased salt concentrations. In the presence of salts in the substrate, plants often accumulate small molecular weight substances called compatible osmolytes. These substances do not interfere with the usual biochemical reactions in the cells. Compatible osmolytes are mainly molecules of imino acid proline and glycine betaine. In the sugar beet, a positive correlation was established between the concentration of free proline and the level of tolerance towards salts. It is believed that under stress, proline plays a role in the osmotic adjustment of cells, protection of enzymes and membranes, but also as a source of nitrogen for the moment when the stress conditions are overcome. The role of glycine betaine is also in maintaining the pH of the cell content, detoxification of the cells and binding of free radicals. Under conditions of salt stress, other nitrogenous compounds such as amino acids, amides, proteins and polyamines can also be accumulated. Their accumulation is often in correlation with tolerance towards salt. Other compatible osmolytes that accumulate are compounds from the group of carbohydrates, namely free sugars (glucose, fructose, sucrose, fructans), but also starch. Their most important roles are in osmotic adaptation, then serve as a reserve of carbon and neutralize free radicals. A similar role is attributed to polyols accumulated in stress conditions.

Plant ionic status is highly correlated with salt tolerance, so it can also serve as a selection criterion in the process of breeding in order to produce genotypes more tolerant to salts.

2.5.6. The influence of salts on mineral nutrition of plants

Increased salt concentrations near the root system can disrupt the mineral nutrition of the plants and limit the yield due to excessive osmotic value or salinity of the soil solution. Excessive salts affect the accessibility of nutrients for plants in many ways. They modify the binding, retention and transformation of nutrients in the soil profile, influencing their uptake and/or absorption by the root system due to ion antagonism and reduced root growth, and disturbance of the metabolism of the nutrients in the plant, primarily through water stress, thereby reducing the overall nutrient use efficiency. In the presence of increased salt concentration there may be some specific symptoms on plants, such as necrosis and burns of the top part of the leaf due to the accumulation of ions Na^+ and Cl^-. High ion concentration may disrupt the structure and function of cell membranes. Changes in the membranes lead to disorders in the chemical composition of the cells and the absorption of nutrients, so symptoms of the deficiency of certain essential elements may occur, just as it does in the absence of salts. For example, Ca^{2+}-ATPase (Ca^{2+}-pumps) have the role of regulating the low concentration of Ca^{2+} in the cytoplasm. Similarly, the regulation of the adoption and distribution of Na^+ and K^+ in plant tissues is controlled by K^+ channels that are highly selective for K^+, and Na^+/H^+ antiporters that transport Na^+ against gradient of concentration. High concentrations of NaCl act antagonistically to the uptake of other nutrients, such as K, Ca, N, P. Increased NaCl concentrations typically increase Na^+ and Cl^- concentration and decrease Ca^{2+}, K^+ and Mg^{2+} in many plant species. Similarly to effects on nutrition with macronutrients, salt stress can also affect nutrition with essential micronutrients. Salts may also exhibit a stimulatory or inhibitory effect on their uptake and metabolism.

It is often considered that the use of mineral fertilizers can complicate problems that already exist due to the presence of excessive amounts of salts in the soil. However, the lack of essential plant nutrients in accessible forms is often the reason for the poor productivity of the saline soils. When the saline soil is washed with large amounts of water for repair, some essential elements can be washed out along with unwanted salts. This requires the application of fertilizers at appropriate rates to compensate for the lack of these elements.

2.5.7. Ionic stress

For each element that is essential (or useful) for plant growth and development, depending on the genotype and phase of ontogenesis, the concentration in tissues may range from acute deficiency to the toxic effect. Knowledge on these threshold values is very important in order to avoid stress caused by inadequate mineral nutrition. The accessibility of nutrients for plants largely depends on the pH of the soil solution which affects solubility of mineral elements. Taking all the essential nutrients together, their solubility attains its maximum values at slightly acidic pH. The genetic specificity of plant nutrition is a very pronounced trait of plants determined by many factors.

Plant features which significantly influence the uptake of ions from the (soil) solution may be grouped in the following manner:

1. Morphological characteristics of the root: type of the root (primary, secondary), its mass, total length, topography, absorption surface, the thickness of root cortex
2. Morphological features of leaves: total leaf area, leaf shaper, thickness, position on the plant
3. Morphological features f stems: diameter, length, number of conductive vessels and their structure
4. The ratio between biomasses of shoots and roots
5. Physiological processes: photosynthesis, transpiration, respiration, distribution of inorganic and organic compounds between different plant parts.
6. Biochemical processes: enzymatic activity, synthesis of organic compounds (sugars, proteins, lipids), concentration of phytochrome, amino acids and organic acids
7. The level of ploidy

Ionic stress can occur if concentrations of different ions in the soil solution are unbalanced. Then an antagonism between different ions may arise, which means that one ion interferes with the uptake of the other. This phenomenon is characteristic of chemically similar ions, because they compete for binding to the same ion transporters located in cell membranes. Therefore, it can happen that, although the concentration of a particular ion in the soil solution is sufficient for plant growth, we may notice the symptoms of ion deficiency because another similar ion is present in the excess and it was therefore preferentially and in excess taken up, thus creating deficiency of the other chemically similar one. There is also the opposite phenomenon, the synergism between ions, which signifies the acceleration of uptake of one ion in the presence of the other and is characteristic of chemically different ions. It is therefore important that the concentrations of all essential ions in the soil solution are well balanced and that ions unimportant for plant nutrition are

Table 2.8. Antagonism and synergism of ions and osmotic stress - specific effects of excess of particular nutrients on the content of the other nutrients

Element in excess	Type of effect	
	Positive (increase in content 15 and more)	**Negative** (reduction in content 15% and more)
N	-	Mg, Co, Mo, B
P	-	N, Ca, Mg, Co, B
K	Mo	N, P, Ca, Mg, Cu, Zn, Mn, Co
Mg	-	P, K, Ca, Mn, Co, B
Cu	Mg, Co, Mn	Mo
Zn	Ca, Mg, Co	-
Mn	K, Zn, Co	Mg, Mo
B	Cu	-

not present in excessive concentrations either. Some of the examples of ions – antagonists are K^+ and Na^+, Ca^{2+} and Mg^{2+}, Cu^{2+} and Mo^{2+}, Mn^{2+} and Mg^{2+}, whereas examples of ions with synergistic interactions are K^{2+} and Mn^{2+}, Cu^{2+} and Mg^{2+}, Zn^{2+} and Ca^{2+}, HBO_3^{2-} and Cu^{2+}, etc.

In conditions of inadequate mineral nutrition (ionic stress) in plants, there are more or less specific symptoms of deficiency or excessive elements. Generally, these symptoms are manifested as lagging in growth, loss of turgor (wilting), chlorosis, necrosis, appearance of spots, premature aging, inability to complete the reproductive cycle, and the like. A great importance has the place on the plant where the onset of the symptoms appears first (younger or older leaves); this is linked to the mobility of a particular ion or its compounds through phloem and the possibility to relocate them from one tissue/organ to another in the plant.

Even though the concentration of salts in the soil solution is not so high to induce visible symptoms on plants, their growth and

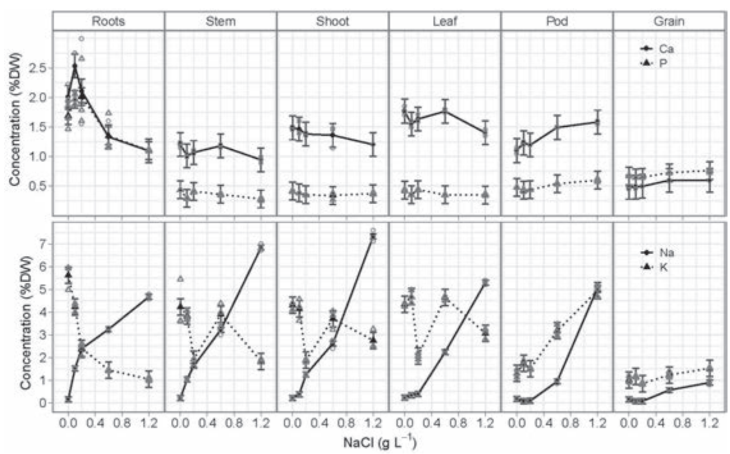


Figure 2.18. Impact of NaCl on the concentration and distribution of Ca, P, K and Na in pea (Maksimovic et al., 2010)

yield may be reduced and chemical composition altered. One example can be seen on the example of pea grown in the presence of different concentrations of NaCl (Fig. 2.18).

2.5.8. Salt (osmotic) stress - conclusion

Soil salinization is important problem in agricultural production.

Harmful effect of salts is visible on the entire plant; even when it is not obvious it may lead to yield reduction and deterioration of quality.

Plant species and cultivars differ with respect to tolerance to excessive concentrations of salts.

Understanding of responses of plant cells and whole plants to salt stress is crucial for stimulation of mechanisms leading to adaptation.

Selection and breeding – both by classic and molecular methods will contribute to better adaptation of plants and increased tolerance to salt stress.

2.6. Impact of heavy metal stress on crop plants and phytoremediation

The variety and quantity of chemical substances that may be found in agricultural soils have increased significantly with the development of the industry. One in a series of pollutants that can be found on the surface and in the fresh vegetable tissues are heavy metals. Crop plants, besides essential, may also contain toxic elements, in a very broad range of concentrations. Accumulation of excess metals in plant tissues can seriously endanger their biochemical quality and usability, even posing a direct threat to consumer's health. Farmers and food processors are more aware of this issue now days than in previous times.

Heavy metals are elements with a specific mass greater than 5 g/cm^3. Among them are essential or useful elements for plants such as copper (Cu), zinc (Zn), manganese (Mn), iron (Fe), cobalt (Co) and molybdenum (Mo) that participate as cofactors or prosthetic groups of enzymes in numerous significant metabolic processes of plants. However, at higher concentrations, all heavy metals, regardless of their physiological role, are very toxic, especially cadmium (Cd), lead (Pb), nickel (Ni), chromium (Cr) and other. Children, especially small, are potentially exposed to greater risk than older children and adults since small children consume more food per unit of body weight than adults.

Table 2.9. Threshold levels of heavy metals in vegetables, soils and irrigation waters *

The concentrations allowed to be present in soils, waters and plant tissues are limited and can be found in legislative. One example of thresholds is given in the following table:

Heavy metal	The highest allowed concentrations of heavy metals		
	Vegetables ($mg\ kg^{-1}$)	Soil ($mg\ kg^{-1}$, total content)	Irrigation water ($\mu g\ L^{-1}$)
Cd	0.05-0.20**	3.0	10.0
Co	50.0	50.0	50.0
Cr	2.3	100.0	550.0
Cu	73.0	100.0	17.0
Fe	425.0	50,000.0	500.0
Mn	500.0	2,000.0	200.0
Ni	67.0	50.0	1,400.0
Pb	0.1-0.3**	100.0	65.0
Zn	100.0	300.0	200.0

*From the following literature sources: 1) FAO General standard for contaminants and toxins in food and feed (CODEX STAN 193-1995) Adopted in 1995 Revised in 1997, 2006, 2008, 2009 Amended in 2010, 2012, 2013, 2014, 2015 4) Ewers, U. (1991) Standards, guidelines and legislative regulations concerning metals and their compounds. In: Merian E, ed. Metals and Their Compounds in the Environment: Occurrence, Analysis and Biological Relevance. Weinheim: VCH, pp: 458-468.; 5) Pendias, A.K., Pendias, H. (1992) Elements of Group VIII. In: Trace Elements in Soils and Plants. Boca Raton: CRC Press, pp: 271-276.
**Threshold values differ for different types of vegetables

2.6.1. Sources of heavy metal pollution

Almost 50% of the amount of lead, cadmium and mercury that is fed into living organisms is introduced through food of plant origin (vegetables, fruits and grains). Because heavy metals, through plants, enter the food chain, the plants play an important role in their circulation in the nature. Knowledge on the ecology and mechanisms of accumulation, distribution and metabolism of heavy metals in plants is therefore of great ecological, scientific and practical significance. Although in most agricultural soils the level of heavy metals is not high enough to cause acute toxicity problems, increased concentrations of heavy metals in food can significantly affect the health of humans and animals. Heavy metals that through food accumulate in a human body, such as Cd and Pb, may be particularly important. The knowledge that mercury (Hg), Cd, and Pb cause numerous diseases and even death in humans have led to more extensive research on the chemical behavior of heavy metals in the soil and their uptake by crop species.

The accumulation of essential heavy metals in the soil, as well as of those with predominantly toxic effects, can be the result of natural processes of decomposition of minerals and rocks during pedogenesis. Therefore, the excess of heavy metals primarily occurs on soils deriving from minerals rich in heavy metals. Soils formed on sulfate, copper, silicate minerals, or on serpentine rocks are characterized by high nickel and chromium content. Too much of the Fe, Mn and Mo is most commonly encountered on poorly drained and flooded soils. High concentrations of heavy metals are noticed on soils with a low pH value. In soil rich in organic matter, the accumulation of Fe, Mn and Mo is more intense whereas in the soils poor in organic matter the content of Pb, Cd, Cu and Zn increases significantly.

Human activities that contribute to the pollution by heavy metals are means of transport, mines, metal industry, smelters, municipal solid and liquid waste etc. The most polluted soils and plants are located near the highways, where lead accumulation accumulated during constant exposure to oil combustion products, especially in a belt up to 10 m away from the edges of the road. Accumulation of Pb in plants depends on a number of factors: plant distance from the main roadway, soil cover with herbaceous plants, length of vegetation and direction and intensity of dominating winds. Leafy vegetables therefore should not be grown at such sites. By using exclusively lead-free fuel, this problem becomes less significant and can be overcome in the future. Dust can also cause damage to plants, if the dust is rich in heavy metals, which is released into the atmosphere in some industrial regions, or smoke that is fueled by exhaust gas engines with internal combustion. Soils and plants in the vicinity of the ore mines and smelters for exploitation of Zn, Cu and Pb are characterized by high content of Cd and Pb. Larger amounts of Cd are also found in industrial waste. Cadmium can occur in increased amounts in the soil by introducing phosphorous fertilizers in which it can be found as a impurity due to the mode of their production. Unlike phosphorus, nitrogen and potassium fertilizers do not contain Cd and are practically non-toxic. Ash, which is an extremely good source of mineral matter for plants, can contain a certain percentage of toxic metals, so it should be taken into account when it is used as a fertilizer. Some previously used pesticides contained as the active ingredient or as impurity, for example, mercury and arsenic. The use of such preparations is no longer permitted, but it is possible that the pollutants that derive from them may have remained in the soil. It is well known that preparations containing Cu are used as an additive in the feed for pigs, which should be taken into account if manure or liquid manure from such stalls are used for fertilization. The regular use of Bordeaux mixture in the vineyards can lead to the accumulation of Cu in the soil. Also, water that is exposed to flooding in areas where industry exists can lead to a variety of pollution, including by heavy metals. Research has shown that at least 20 million hectares in the world are irrigated with wastewaters, mainly in leafy and other vegetables. As a consequence, heavy metals are accumulated both in soils and in plants. Metals such as Pb, Cd, Cu and Hg are cumulative toxins and pose a hazard to the environment due to their exceptional toxicity.

2.6.2. Uptake of heavy metals and their impact on plants

Plants take up metals predominantly by absorption from the soil solution but sometimes also through their above-ground organs. The presence of higher concentrations of heavy metals in the soil is very harmful to the plants. They can lead to morphological and anatomical changes but also significantly affect the physiological processes. As a result, the biomass productions is reduced and the chemical composition of the plants is changed. The basic effects of toxic concentrations of certain heavy metals such as Cd, Cu, Pb and Zn are more or less specific, depending on the physical and chemical properties of their ions and organic complexes which they may form in the soil. The most frequent changes they induce in plants are linked to alterations of the activities of enzymes, cell membrane damages and decreased root growth. That is why there are also disturbances in water regime, phytohormone activity, and the uptake of nutrients. Photosynthesis, transport of organic compounds from their sources to sink and also respiration process are obstructed. Geese plants may occasionally accumulate significant amounts of heavy metals, and that no apparent symptoms of their damage occur. Often, there is not much reduction in yield or reduction of organic matter production. Only when their concentration exceeds a certain limit causes disturbances occur in all life functions, i.e. decreases in organic mass formation, but the quality of products and their biological value comes much earlier. Under certain conditions and in some plants, smaller quantities of nonessential heavy metals can stimulate the growth of plants.

The intensity of uptake and accumulation of heavy metals in plants depends on numerous factors and is not yet completely clarified. Generally speaking, the uptake of heavy metals increases with the lowering of the soil pH value, by reducing the content of organic matter in the soil and by the increase in the concentration of soluble forms of heavy metals in the soil. Metals such as Fe and Cu are, in principle, the best soluble in a weak acidic medium ($pH < 7$), and their solubility increases with a pH decrease. Other metals, such as Al and Zn, are more soluble in the basic environment, especially when the pH is above 10. In the weak acidic medium (pH 4.5-6.5) Fe and Cu have low solubility both in extremely anaerobic and aerobic conditions. The reason for this is the formation of sulfides having low solubility under very anaerobic conditions, as well as the formation of low soluble hydroxides and oxides of metals under very aerobic conditions. Uptake of heavy metals by plants depends significantly also on the processes in the rhizosphere and the application of organic fertilizers, phosphate, lime, soil temperature, light intensity, and genotype specificities.

Plants can uptake heavy metals by variable intensity. Species that can, without the obvious symptoms, absorb and accumulate large amounts of heavy metals are often referred to as "metalophytes", "hyperaccumulators" or heavy metal flora. The term "heavy metal flora" comprises plant species that normally develop and grow on soils which are enriched with heavy metals either by natural processes or by anthropogenic activities. Among them there are no cultivated crop species. They are mostly susceptible to the presence of higher concentrations of heavy metals

Reduction in the biomass production in plants in the presence of higher concentrations of heavy metals results from their adverse effect on photosynthesis, but also on the entire metabolism and energy turnover in plants. At the same time, due to the appearance of necrosis and the loss of individual organs of plants, loss of already synthesized organic matter is lost. Heavy metals, especially non-essential, accumulate much more intensively in the roots than in the shoots. Individual elements such as Cd and Ni are rapidly transported to the shoots after their uptake by roots. The accumulation of heavy metals in certain organs and tissues is primarily conditioned by the tolerance mechanisms of plants against heavy metals and their direct or indirect interference with certain physiological and biochemical processes. Individual plant species, depending on phonological phase, the pH value of the medium, the substrate type, and the like, may react differently to the presence of higher concentrations of heavy metals. It was found that significant differences exist in the reactions of different genotypes of the same species in the presence of heavy metals. For example, it was found that the roots of a single carrot genotype contained twice as much Pb as the other, when they were cultivated on the same soil, contaminated with this metal. Unlike Pb content, Cd content was much less varied in the roots of different carrot varieties. Numerous researchers have proven that high concentrations of heavy metals differ in plant species at certain stages of development and can vary in their chemical composition and seed yield. The effect of heavy metals on plant yield can be altered by many external factors. It was found that magnesium and sulfur can mitigate the adverse effects of high concentrations of Cd. Cumulative effect of a large number of heavy metals was found, for example, Cd, Cu and Ni. They usually reduce the yield much more than if they would individually at the same concentration. The effect of heavy metals also depends on the type of soil, mostly on its pH and the content of organic matter. Heavy metals may affect root anatomy (Fig. 2.19).

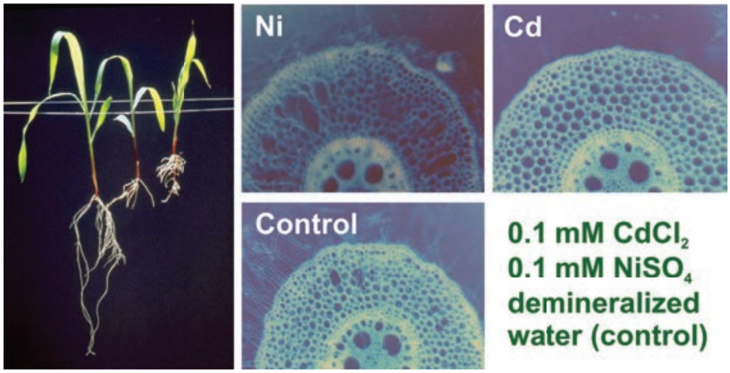


Figure 2.19. The effects of the steady presence of Cd and Ni on young maize root anatomy (I. Maksimović, orig.)

For years, in Vojvodina, the content of certain metals in soils and cultivated plants is monitored. Soil mapping has shown that our soil is healthy - unpolluted with heavy metals, and by nature of exceptionally good quality. The pollution of our soils with heavy metals is happening locally, which should be monitored and if needed, carry out remediation which means „cleaning“ of such soils.

More recently, great attention is paid to the study of the effects of higher concentrations of heavy metals on the metabolism of plants and to breeding of genotypes tolerant to their excessive concentrations, which would also be characterized by lower accumulation of heavy metals. At the same time efforts are being made to detect species and genotypes of hyper-accumulators to be used for the decontamination of soil contaminated by heavy metals.

Publicity that has a high level of heavy metals in the environment in general, even in food, can sometimes cause concern and even fear among the population. Consumers are increasingly aware that the food they consume daily, especially vegetables and fruits, may contain heavy metal concentrations that are above the threshold levels. It is therefore essential that such fresh-state products are regularly analyzed (monitored) to make sure that the concentration of undesirable heavy metals is no higher than internationally accepted standards. Cadmium and lead are among the most widespread heavy metals and they are extremely toxic. The high concentration of these metals in food is associated with the development of numerous diseases, especially cardiovascular system, kidney, nervous and bone tissue. It has been proven that these heavy metals are carcinogenic, mutagenic and teratogenic. Other heavy metals, such as Cu and Zn, are necessary for biochemical and physiological processes in the body and are essential for the maintenance of health throughout their lives.

Mechanisms that allow plants to sustain increased concentrations of heavy metals can be divided into two groups (exogenous and endogenous), each of which contains sub-groups:

Exogenous (apoplastic) tolerance mechanisms:

- Mobilization in the cell wall
- Exfoliation of the cheat
- Establishing a pH barrier
- Ectotrophic mycorrhiza

Endogenous (symplastic) tolerance mechanisms:

- The chelate and polypeptide-phytochelatine activity in the cytoplasm
- Compartimentation and creation of complexes with organic and inorganic acids in vacuole
- Binding with phytic acid
- Heat shock proteins ("Heat shock proteins")

Other protective mechanisms

- Reduction of plasma membrane permeability for TM
- Reduced adoption of TM
- Binding TM to root
- The presence of other ions in the soil (Si, Ca-Mn; P-Pb; S-Cd)

2.6.3. Possibilities for reducing the contamination of plant tissues with heavy metals

Methods to reduce the concentration of heavy metals in plant tissues are focused on the modification of soil pH, the content of organic matter in the soil, the responsible and rational use of mineral fertilizers, and the cultivation of suitable species for the properties of given soil and microclimate. Interactions between soil and plants as well as between the root system and the soil microflora are also very important because they influence the movement of heavy metal ions from the soil into edible parts of vegetable crops. An agricultural practice involving simultaneous consideration of fertilization methods, application of irrigation water of appropriate quality and rotation of crops can affect the accessibility of heavy metals to plants and their final quantity in plant parts. Organic matter binds a large proportion of heavy metals and thus reduces their accessibility to enter plants. However, over a longer period of time, they will again flow into the soil solution. Compost rich in phosphorus and phosphorous fertilizers can reduce lead absorption through the root system. The acidity of the soil (pH) should be about 6.5-7.5. Using the technique of mulch, other than the other advantages provided by this method (e.g. preserving the soil moisture) can reduce the build-up of dust (tiny particles of soil) that may sometimes lead to inhalation of lead that is otherwise in the soil, especially if it is nearby roads heavily loaded with traffic.

2.6.4. Phytoremediation

Phytoremediation (Phyton - Plant and Remediare - Leave) is a technology for purifying contaminated soil and water by cultivating plants that can degrade, extract, retain or immobilize contaminants present in the soil and water.

Table 2.10. Fundamental processes involved in phytoremediation of contaminated and polluted soils

Process	Effect of pollutant	Targeted pollutants*
Phytostabilization	Inactivation	**HM**, MO, HA, **RA**, OR
Phyto immobilization	Inactivation	**HM**, MO, HA
**Phytoextraction	Removal	**HM, MO, HA, RA**, OR
Phyto volatilization	Removal	HM, **MO**, HA, OR
Phyto degradation	Removal	**OR**

*HM-heavy metals, MO-metalloids, HA-halides, RA-radionuclides, OR-organic pollutants
**Phytoextraction includes phytomining

Although this is a relatively new technology, the very concept of using plants in the remediation of contaminated habitats dates back 300 years ago. However, it has long been forgotten due to the lack of understanding the transport of ions in the plant and mechanisms of plant tolerance. Interest in phytoremediation has risen again after finding plant species that are metal hyperaccumulators. Hyperaccumulators are plants that have the ability to accumulate and retain large amounts of metals, and have a high bio-accumulation coefficient. The first plants found to accumulate high concentrations of metal in the leaves are *Thlaspi caerulescens* and *Viola calaminaria*.

The efficiency of phytoremediation may be expressed as the coefficient of phytoextraction which is calculated as a ratio between concentration of heavy metals in plant dry weight (mg HM/g) and concentration of the same heavy metal in the substrate dry weiht (mg HM/g).

2.6.4.1. Advantages and disadvantages of phytoremediation

The application of the soil phytoremedation of heavy-metal contaminated soils has a number of advantages. In addition to being one of the cleanest and cheapest technologies, secondary pollution is avoided, it can be applied to all heavy metals, and metal-rich plant residues can be recycled. In addition, the application of phytoremediation has very significant side effects, the plant cover can reduce or prevent soil erosion, the planting of woody plants creates windproof belts that can reduce wind and noise in the region, and also create new habitats for development of fauna, etc.

However, there are some limitations in the application of this technology. The primary limitation for the application of phytoremediation is the root system of plants. Namely, for phytoremediation it is necessary for polluting substances to be in contact with the root zone, therefore it is realistic to expect a decrease in the concentration of pollutants in the zone up to about 1 m away from the root. In addition, the mobility and accessibility of heavy metals to plants depends on many factors, such as the pH of the soil, the content of organic matter and clay in the soil. Low pH, lower content of clay and humus accelerate the uptake of heavy metals. Knowledge of these factors and their control are necessary for the successful phytoremediation of soil contaminated with heavy metals. Additional procedures are often necessary, such as application of chelators that facilitate the uptake of heavy metals by the plants. The growth rate of plants is also a significant limitation, which also involves a long period of soil remediation with this technology.

Phytoremediation is suitable for use in areas with low to moderate levels of soil contamination. High concentrations of heavy metals can inhibit the growth of plants, and therefore limit the application of this technology. There is a great danger of the entry of heavy metals into the food chain through contaminated plants, which requires application of appropriate control measures within this technology. Selecting the species to be used in phytoremediation is a critical step that determines the success of the entire procedure. Therefore, the knowledge of the uptake, accumulation of heavy metals in plants, as well as the anatomy, morphology and physiology of plants is of utmost importance for the application of these procedures for the repair of soil and water quality.

The desirable characteristics of the genotype suitable for phytoextraction are:

1) Tolerance to high concentrations of TM,
2) Intensive accumulation of one or more TM,
3) Possession of a high transfer factor,
4) Intensive transport of TM into the above ground organisms,
5) High production of biomass (t / ha / year),
6) Genotype adapted to given edaphic and climatic conditions and
7) Absence of requirements for special cultivation technology.

2.6.4.2. Conclusions on phytoremediation

- Many laboratory and field studies have confirmed that the practical application of plants for soil HM clean-up is possible.
- The success of phytoremediation depends first and foremost on the plant species used, its capacity for HM accumulation and translocation to shoots, its biomass pro-

duction and measures used to promote HM accumulation in plants.

- Results suggest that some crop plants could be used for clean-up of HM-polluted soils.

Part 3 – Crop management in changing climate (examples for forage crops)

3.1. The role of cover crops for enhancing sustainability of cropping system

The intensification of agricultural practice during the second half of the XXth century, with more inputs (such as fertilizers, pesticides, irrigation) allowed significant yield improvement in most arable crops. However, at the same time, these types of farming systems, together with other human activities, have contributed many negative environmental impacts leading to several risks or damages: greenhouse gas emissions, a consumption of fossil energy, the high use of pesticides and the use of increasing amounts of water for irrigation which contributes to the depletion of underground water. Arable crops are responsible of half of the world N_2O emissions. The higher use of mineral nitrogen (N) fertilisers is linked to an agricultural product and is also the major source (70 to 90%) of N_2O emission and the higher use of pesticides leads to contamination of water, air and soils with risks of toxicity.

The use of cover crops is one measure that has been taken in agricultural production in order to increase environmental protection and to encourage sustainable use of natural resources. Farmers and researchers are using cover crops to design new strategies that preserve farms natural resources while remaining profitable. The key to this approach is to observe farm-agro-ecosystem unity and establish agricultural production on environmental, economically feasible and socially acceptable principles.

Cover crops are crops grown between two cash crops. Cover crops can be a pure stand or mixture of crops. In temperate region, there are suitable conditions for growing annual winter cover crops after a cash crop harvest in late summer/autumn and before the next cash crop is planted the following spring. The species from the family of legumes (Fabaceae), grasses (Poaceae) and crucifers (Brassicaceae) are commonly used as winter cover crops and a pre-crop for cash crops such as maize and industrial crops. The dominant cover crop species in temperate region are forage crops i.e. field pea, vetches, small grains and the mixture of those crops. On contrary, in tropical region cover crops are usually grown for several purposes. The most common are grain legumes like cowpea (*Vigna unguiculata*), mung bean (*Vigna radiata*) and chickpea (*Cicer arietinum*), and of perennials are creeping peanut (*Arachis pintoi*), calopo (*Calopogonium mucunoides*), centro (*Centrosema pubescens*), kudzu (*Pueraria phaseoloides*), siratro (*Macroptilium atropurpureum*), stylo (*Stylosanthes guianensis*) etc. The usual tropical cash crops following the named cover crops are maize and sorghum.

There are numerous benefits that cover crops offer to sustainable agriculture and the main benefits include:

- cutting of fertilizer costs (omit fertilizers),
- minimizing greenhouse effect,
- reduced need for pesticides,
- improved yield by enhancing soil health,
- prevention of soil erosion,
- conservation of soil moisture and prevention of nutrient leaching,
- water quality protection.

Benefits vary by location and season and are highly related to the weather conditions, but at least two or three occur with any cover crop. In addition, the main benefits of cover crops can be only achieved with careful selection of appropriate species. For ecological reasons, legumes are gaining increasing importance, since nitrogen use in arable lands is the cause of several major environmental problems, and since additional nitrogen is needed by all arable crops except legumes. The application on mineral nitrogen fertilizers required by the non-fixing crops induces a greenhouse effect two to three times higher per hectare than with a legume crop. The absence of nitrogen fertilizer on the legume crop and the reduction of fertilizer amount required by the following crop, due to highly efficient nitrogen mineralisation, allow a significant reduction of fossil energy consumption and of greenhouse gas emissions. For example, in the Barrois region in France or Saxe-Anhalt in Germany showed a reduction of 50% for energy consumption of a pea crop compared with oilseed rape, wheat or barley crops, leading to an average reduction of 13% for a rotation which includes 20% of legumes and 50% for the greenhouse gas emissions for the pea crop compared with the other crops. Thus, the use of legumes in crop production may have a significant role in terms of environmental protection.

In annual cropping systems, cover crops are often included to maximize benefits, such as increased biomass and nitrogen production. Cover crops can increase yield and at the same time, they can reduce costs, increase profits and even create new sources of income. The practice of cover cropping in some regions has gained importance in view of the decline of animal production and reduced availability of organic fertilizers. Besides the natural content of nutrients that are present in the given soil, plants can be provided with the necessary nutrients by applying mineral fertilisers, or by introducing organic fertilisers, growing cover crops etc. In the Vojvodina province, Serbia, fertile soils such as chernozem have suffered a significant reduction in organic matter content, in some cases as much as 50%, which justifies the introduction of cover cropping in agricultural production. According to the results of complex research carried out in 1993 and its comparison with the results of the land analysis carried out in 2000, in Vojvodina the decline in organic matter content averagely amounted to 0.38% and about 2.7% of the land has very low organic matter content, while 26% of the samples contain 1.5-3% organic matter.

One of the biggest challenges of cover cropping is to fit cover crops into current rotations or to develop new rotations that take full advantage of their benefits. Selection of cover crops is much easier when the crop rotation or cash crops have already been determined. Cereals, legumes, oilseeds are often used as cover crops, as sole crops or as a mixture. Legumes have many benefits, they help to control weeds, improve soil structure with their roots, supply soil with nitrogen, and thus are suitable for crop rotation. Legume cover crops can be easily included in a crop rotation and together with fallow, planting density, time of planting, irrigation etc. represent an agronomic option for combating increasing temperatures and incidence of drought, induced by climate change. Legume cover crops contribute additional nitrogen to the nutrient cycle by symbiosis with *Rhizobium*. By ploughing-in 30-40 t ha^{-1} cover crop biomass, 100-200 kg N ha^{-1} is incorporated into the soil. Most of the symbiotic N is used for legume growth and, therefore, is accumulated in organic matter. Some of this N can be used later as animal feed in the form of protein in herbage, while the rest of the accumulated N can be taken up by subsequent crops after ploughing-in and mineralisation of the organic matter. It is important to emphasize that in favorable conditions (soil pH, temperature, moisture) the activity of *Rhizobium* is higher and thus the amount of biologically fixed nitrogen as well.

Legume-cereal mixtures show great potential over a wide range of niches. Legume-cereal cover cropping may enhance above and below ground biomass yield and carbon (C) and N content. The increase in C and N supply to the soil has the potential to improve soil quality and crop productivity compared with monoculture cover crop species. Cover cropping can promote root growth of the succeeding crop compared with no cover cropping by increasing the amount of plant residue returned to the soil, thereby increasing soil organic matter level, decreasing bulk density, influencing soil temperature etc. Tillage can interact with cover crop and N fertilization in crop root growth. Reduced tillage plus carbon inputs from residues increase soil organic carbon. Grasses contribute more carbon than legumes due to a higher C/N ration. Their residues decompose slowly, and soil nitrogen availability may be substantially decreased following their incorporation into the soil. Growing plants tend to maintain soil organic C level by continuously supplying C from roots compared with bare soil, which tends to decrease it. Cereal cover crops produce the largest amount of biomass and should be considered when the goal is to rapidly build soil organic matter. Most nonlegume cover crops do not fix nitrogen, but they can affect soil nitrogen availability. Small grains can absorb large quantities of nitrogen from the soil, thereby reducing the potential for nitrate leaching. Several species in the *Brassicaceae* family also readily take up nitrogen. Due to lower C/N ratios, however, these species decompose and release their absorbed nitrogen into the soil more rapidly than grasses.

For adequate establishing and use of cover crops, it is necessary to identify a goal, a time and a place, as well as the desirable characteristics of cover crops. Improper management of cover crops can lead to substantial yield loss of cover crop as well as the subsequent cash crop. Since cover crops have different functions, it is important to determine what the crop is expected to do. Thus, fitting a cover crop into the sequence of a crop rotation must be taken into consideration. Fast-growing, drought-tolerant cover crops that require minimal management are preferred. Cover crops with fast germination and good seedling vigour are usually chosen because of their ability to compete with weeds. Also, species with the potential to reduce pest populations should be chosen, while those that harbour harmful diseases or pests of the cash crops should be avoided. Fast-growing cover crops such as grasses/cereals and crucifers hold soil in place, reduce crusting and protect against erosion due to wind and rain. They can be grown whenever the soil is left bare for part of a season. For example, after the harvest of the main cash crop, more cover crops can be planted and provide cover throughout the winter. Furthermore, common vetch once established forms an excellent living ground cover and thick mulch after it dies. The hairy vetch or mixture with rye or another small grain can reduce erosion, to add N and organic matter to the system. Rye provides soil protection on sloping fields and holds soil loss to a tolerable level and the spring barley holds soil strongly to minimize erosion during drought.

Soil compaction continues to be a major problem for farmers in intensely cropped areas. The urgency of timely field operations, accompanied by unpredictable precipitation, often results in heavy equipment traffic on wet soils. It was reported that limited root penetration on compacted soils aggravated the effects of drought in reducing soybean yields. Soil strength increases with compaction, especially during the summer when compacted layers in the soil become dry and hard, therefore, roots are less able to penetrate deeply enough to access the water and nutrients stored in the subsoil. Cover cropping can promote root growth of the succeeding crop compared with no cover cropping by increasing the amount of plant residue returned to the soil, thereby increasing soil organic matter level, decreasing bulk density, influencing soil temperature, and increasing the density of bio pores in the soil profile where roots of succeeding crops can grow even in the root restricting layers. In some researches, it was observed increased root growth of soybean in root channels made by decomposing cover crop roots in the compacted soil, which increased soybean yields even during drought condition. Deep-rooted cover crops are one possible solution to compaction problems, especially in no-till farming systems. Those cover crops can alleviate soil compaction problems by establishing root channels that increase soil infiltration rate, which benefited root systems and yields of the main crops. For example, the deep growing tap roots of the perennial alfalfa can increase infiltration rate on compacted no-till soils, and root channels left by alfalfa have been shown to benefit corn root systems that follow.

Replacing bare fallow with cover crops may enhance the aggregate stability and water retention capacity of the soil, which are two important characteristics in irrigated land. Nevertheless, cover crops increase evapotranspiration and reduce water percolation beyond the root system during the non-growing season, therefore, they could lead to salt accumulation in the upper soil layers. A long-term evaluation of potential salt accumulation in the soil profile is, therefore, necessary to ensure that the potential disadvantages originating from soil salt accumulation are compensated for by the advantages of cover cropping. For example, if the fallow is replaced with a cover crop the salt leaching in irrigated maize crop is reduced below 1.2 m in depth. This is because the fallow is more prone than the cover crops to accumulate salt in the soil profile during the intercrop period. This effect could be attributable to the enhanced salt dissolution in the fallow treatment (owing to its higher water content) increasing the potential for salt accumulation. This beneficial effect of cover crops on soil salinity may be relevant in cropping systems in which salt accumulation is a problem, particularly because subsequent cash crops are more sensitive to soil salinity in their early growth stages.

Cover crops dramatically reduce surface water runoff and increase soil moisture retention as a result. Rain on bare soil does not penetrate into depth and upon impact, rain drops compact the particles on the soil surface. This forms a crust through which more rain does not penetrate, and it runs off instead of that. Cover crops allow rainfall and snow melt to be absorbed, and allow the soil to hold plant available water longer – like a spongy reservoir in the porous root zone. Cover crops create good soil structure, with a good balance between micro and macro pores that take in and release water and air in accordance with the crop requirements.

Cover crops can be grown in the rotation after harvest of the main crop, or they could be grown simultaneously during a part or the entire growing season of the main crop. Interest in the use of cover crops has been motivated primarily to produce crops in a more environmentally manner. Cover crops are usually chosen according to their ability to compete with weeds and potential to suppress pests and diseases. Seed germination of weeds depends on adequate water supply, optimum temperature, and light. Cover crops residue remaining on the soil surface can physically change germination environment by intercepting light and rain and interfering the heat and water transfer between the soil and atmosphere. Researchers indicated that changes in the light spectrum reaching the seed under plant residue could affect the light quality, thereby suppressing germination and growth of photo-dormant species. Plant litter on the soil surface may retain some rain water, thereby limiting the amount of water for germination. In addition, plant residues may lower the soil surface temperature by acting as insulation from the air temperature and intercepting solar radiation thus delaying cooling of the soil surface more than heating. The residues on the soil surface may obstruct seedling roots reaching the soil thereby reducing the growth of seeds and sprouts. Once the stored resources of the seed are depleted no energy is available for growth. The degree of weed control provided by the residues is likely influenced by the weed species and growth stage, the thickness of soil cover and the soil type.

In integrated pest management cover crops have a significant role. The key in achieving this kind of pest management is to conserving and encouraging beneficial organisms. Cover crops have influence on the soil health improvement which leads to a higher biological activity, reduced pesticide application, cutting of production costs, protection of agro-ecosystem and increase of consumer trust.

Cover crops have economic and environmental benefits, but it is important to understand their potentially negative effects on aspects such as crop quality and yield through the alteration of soil moisture. Poor management of cover crop systems could result in undesired consequences in regard to soil moisture. While cover crops may increase water infiltration into soil and soil water holding capacity, they also use water to grow and can potentially reduce yields of the subsequent crop in rain-fed semiarid regions by reducing soil water content at planting. This is less of a problem in humid areas and where irrigation water is available to make up for water deficits at planting time. Summer water conservation by cover crop residues may be more important than spring water depletion by growing cover crops in determining final yield if early season water deficits do not delay crop establishment. The early killing of the cover crop is a management alternative that can improve soil water management where risks of N leaching are minimal.

While different cover crops have varying effects on the soil-water balance, the general trend is for the crops to dry the soil more than a control plot kept free of vegetation. In some situations, cover crops can dry the soil significantly beyond desirable levels for growing plants. While drying of the soil is occasionally desirable, it can be directly detrimental to cash crop yield or to increase plant stress that in turn decreases yield. In extremely drought years (growing seasons) with a specific schedule of precipitation effect of cover crops on cash crop could be very negative. The decision to use a cover crop during the season must include consideration of the water requirements of both, cover crop and cash crop.

Cover crops can be grown for forage, grain or as a green manure, depends on the farm organization and it works well in systems with multiple crop enterprises and livestock. Cover crops could be used also as green manures that are grown and tilled under to add nutrients and improve the soil properties. Selecting a single species is often popular among farmers due to the ease of planting, uniform development, and predictable termination efficacy of the cover crop. However, often a combination of cover crops is better than planting one alone and species mixtures for cover cropping show great potential over a wide range of niches. Multi-species mixtures may increase productivity, stability, resilience, and resource-use efficiency of the cover crop community. As mentioned, cover crops can be used as living mulches around or beside cash crops for weed control, to reduce soil erosion and conserve soil moisture by reducing evaporation, but they can also be used as catch crops which are planted to 'catch' excess nutrients that might otherwise be leached from the soil.

3.1.1. Effect of cover crops on subsequent crop

Use of cover crops has benefits for both, the soil and the subsequent crop. After mineralisation of ploughed-in cover crops, accumulated N is available for subsequent crops in the field crop rotation. When a legume cover crop is incorporated into the soil, a substantial amount of nitrogen is usually mineralised within a few weeks, and the nitrogen continues to mineralise in ensuing weeks as the organic matter decomposes. Recently, the emphasis has been placed on the uptake of soil mineral N which could otherwise be leached as NO_3 into deeper soil layers and groundwater, lost during nitrification as NO and N_2O, or denitrified as N_2. The contribution of symbiotically fixed N by winter legume cover crops to the nitrogen cycle in field rotation can exceed one hundred kilos N per hectare with beneficial effects on the succeeding crop in the rotation.

In two-year field experiment carried out in Vojvodina Province, Serbia, the effect of cover crops grown as green manure on the dynamics of NO_3-N in the soil, before and after ploughing-in of the cover crops was studied. The additional goal of this trial was to assess the effect of the cover crops on the yield and quality of Sudan grass. Three sole cover crops and one mixture were included in the experiment - wheat, field pea, oilseed rape, and the mixture of field pea and wheat, as well as mineral fertilization treatments, namely 40 kg N ha^{-1} (N_1) and 80 kg N ha^{-1} (N_2) and an unfertilized control. It was concluded that cover crops and N treatment significantly affected the soil Nmin content. At the first two sampling dates-before cover crop sowing and at the beginning of the spring growing season of the cover crop, soil nitrate content was higher in the non-cropped treatments i.e. in the control (bare fallow) and the mineral fertilization treatments. This can be explained by the fact that, when sampled, these treatments had no plants that could uptake N from the soil. The lowest soil Nmin content was in winter wheat and its mixture with field pea as a consequence of intensive N uptake by the plants. After the first and second cut of Sudan grass, results of soil sampling has shown that the treatment with winter field pea had the highest Nmin content. This is a result of intensive mineralization after the ploughing-in of the legume crop and it's due to significant removal of N by the Sudan grass yield in other treatments. The lowest soil Nmin content was recorded in the treatments with winter wheat, crop mixture and the crucifer, which also had the lowest yields of Sudan grass. The yields of Sudan grass following the addition of N_2 and field pea cover crop were higher than the control, while they were on the same level as the control after cover crops of oilseed rape and the mixture of wheat-field pea. Wheat produced the lowest yield of Sudan grass, due to nitrogen deficiency after ploughing-in. The N_2 treatment had the highest crude protein content at the first cut and the lowest at the second cut. Non-leguminous cover crops, which typically have low N content, show little or no beneficial effects on the succeeding crops and in some cases, the effects are even negative. The reasons for possible negative effects of cover crops on the succeeding crops in field rotation are also soil moisture depletion by cover crops in spring, or in some cases because of the allelopathy. Water use by cover crops can adversely impact yields of subsequent dryland crops in semiarid areas. Despite concerns about water use, many farmers are interested in cover crops because of the potential for improved nutrient cycling and biological N2 fixation. Agricultural practices involving cover crops, such as species, fertilization, kill date, and tillage significantly affect subsequent crop yields. In the mentioned research the field pea cover crop achieved the highest dry matter (DM) and N yield. Thus, having in mind that cereal cover crops produce a higher amount of biomass and should be considered when the goal is to rapidly build soil organic matter. But, for enhancing cash crop yields, legume cover crops are the most reliable means compared with fallow or other cover crop species. The management decision concerning the use of cover crops should be based on the balance between farm profitability and environmental sustainability. In animal production areas, cover crops can be an important source of quality forage or can be used for mulching. In such cases and in rotation with Sudan grass, cover crops should fulfil the following requirements: low-cost production, yield, and quality, N uptake during periods critical for leaching and no negative effects on subsequent crops.

Another research has been carried out concerning the effect of cover crops on subsequent crop. The aim of this trial was to analyze the effect of different winter cover crops on the dynamics of NO_3-N in the soil, before and after ploughing-in and on yield and yield components of silage corn. The experiment was conducted during 2011-2013. The experiment included two sole crops-common vetch, triticale, the mixture of common vetch and triticale and mineral fertilization treatments, namely 40 kg N ha^{-1} (N_1) and 80 kg N ha^{-1} (N_2) and an unfertilized control (Picture 2). The same methodology was applied at three locations in the north part of Serbia, Sombor, Senta and Novi Sad. Before cover crops were cut and plough in (Picture 2), analyses of soil samples had shown that soil nitrate content was higher in treatments without crops, in the control (bare fallow) and the mineral fertilization treatments. This can be the effect that there were no plants that could uptake N and moisture from the soil. The lowest soil Nmin content was in triticale treatment since the other two treatments had legumes which uptake nitrogen via *Rhizobium*.

Growth and yield of silage corn were significantly affected by low precipitation and high air temperatures in late spring and during the summer, as well as water consumption of winter cover

Picture 3.1. Different winter cover crops (Photo, Vujic S., 2013)

Picture 3.2. Cover crop mulching and ploughing-in (Photo, Cupina B., 2012)

crops. Before silage corn was sown treatments with winter cover crops had lower moisture content up to 6% relating to treatments without crops (Picture 3). In these treatments, yield was reduced and there was no removal of nitrogen (Picture 4). The nitrogen content in September has increased in all treatments, but the increase was more expressed in the block where the mass was ploughed-in. This is a result of a certain amount of moisture contained in the ploughed plant material that has enabled greater microbial activity and its decomposition.

However, due to a lack of rainfall corn was unable to take nitrogen or to be leached in deeper layers. Treatment with vetch and tri-

Picture 3.3. Effect of cover crops on the soil moisture content (plots after cover crops are light brown) after ploughing (Photo, Cupina B., 2012)

ticale mixture had the highest increase in nitrogen content (over 70 kg ha-1) in both blocks because of a more balanced C: N ratio of a ploughed mass. Like in previous research, the lowest soil Nmin content was in treatment with cereal as a consequence of intensive N uptake by the plants. In those treatments yield of the subsequent crop was the lowest. Many studies have shown that cover crops have a beneficial effect on succeeding crop. But, in semiarid areas, as well as in temperate regions without irrigation with dry and hot summers and hard winters, using cover crops can limit the yield of cash crops.

3.1.2. Cover crops for establishing perennial legumes

Perennial legumes, such as alfalfa and red clover, represent important sources of forage. They can be established either in

Picture 3.4. Detrimental effect of cover crops (caused by soil moisture depleting) on cash crop (silage maize) (Photo, Cupina B., 2012)

summer/autumn or in spring. In temperate regions, late summer or early autumn sowing is usually followed by high temperatures and lack of moisture which causes problems in establishing. A spring-sown crop has often a significantly lower yield in the year of establishment which could be partially explained by weeds which are a much greater problem in a spring-sown crop. The difficulty in obtaining an economically significant yield from perennial forage legumes in the year of establishment has forced the farmers to establish these crops with a cover-companion crop. Cover crops here are used to cover the soil between the rows of perennials and thus to enable weeds to develop, and to increase the first cut yield. The establishment of perennial crops with cover crops is done using intercropping as a growing technique. Intercropping is the simultaneous growing of two or more crop species in the same field where crops tend to use ressources in a complementary way and then more efficiently than sole crops. The mechanism of weed reduction, where one of the crops in the mixture provided an environment that reduced weed biomass. This would thereby allow the other component species to out-compete the weeds. In those situations, where companion cropping is used to establish perennial forages, this is a frequent case. However, it must be clear that a companion crop does not have to compete too long with the undersown crop in order to avoid damage to the latter.

In the West Balkan Countries and beyond, it is small grains, primarily oats and barley that are traditionally intercropped with perennial legumes, although these tend to be too fast-growing and therefore too competitive for the legume component. Such companion crops compete with weeds, but also with the undersown species, reducing yield and in some cases the persistence of the stand. To enable adequate competition among the intercropped plants, it is recommended that the normal seeding rate of the companion crop be reduced. Annual legumes such as field pea and vetches are suitable for intercropping with perennial forage legumes because the crop can be harvested quickly and the canopy structure is not dense enough to cause suppressive shading. Because of its short growing season, field pea and vetches are suited to be harvested when the first (establishment) cut of perennial legumes is due. Cultivars of field pea with semi-leafless leaves and with short stems could be more adapted for intercropping since the light penetration is much stronger, providing better conditions for the initial growth of the undersown crop. In addition, including peas in this arable mixture makes possible to improve forage quality and digestibility, that is, to increase the forage crude protein content and to decrease both neutral (NDF) and acid (ADF) detergent fiber.

3.1.3. Conclusion

Cover crops can affect subsequent crop yield and amount of nitrogen left in the soil in different ways. In extremely low precipitation years in semi-arid dry land cropping systems inclusion of cover crops in cropping system caused decrease soil water availability to subsequent crop and thereby decreasing its yield with insufficient release of nitrogen during the main crop growing season. In average year winter cover crops in annual crop production systems can provide both effects on subsequent crop as well as nitrogen conservation. To ensure security of such production, especially in temperate climates, it is recommended to use irrigation in silage corn production in the subsequent sowing. Otherwise, highly variable weather conditions in temperate region with inadequate precipitation and in short growing seasons can make crop production with cover crops included risky. However, even though inclusion of winter cover crops depends on environmental conditions, it is a useful practice for crop rotations. The some benefits of cover crops are important for a long period, having in mind that enhancing soil quality i.e. primarily organic matter content requires time to build up. Using mixtures, especially legume-cereal is a very effective strategy for the management of winter cover crops, because cereal and annual legume complement each other very well, as the cereal is capable of high growth rates during the cold season, while legume becomes very important in spring, when N becomes the limiting factor.

It is urgent to change cropping systems in temperate region in order to achieve the environmental requirements of a more durable development.

3.2. Legume-based intercropping systems

Intercropping represents a simultaneous growing of two or more crops in the same field without necessarily sowing and harvesting them together. This farming technique can be considered as a practical application of ecological principles based on biodiversity, plant interactions and other natural mechanisms. Intercrop components tend to use resources in a complementary way and more efficiently than sole crops. However, to accomplish this important intercropping concept must to be satisfied, i.e. when two or more crops are grown together, each must have adequate space to maximize cooperation and minimize competition between them. This includes spatial arrangement, plant density, plant architecture and maturity dates of intercrops.

Intercropping can be applied through several patterns - mixed, row, strip and relay. The mixed intercropping is a growing two or more crops simultaneously with no distinct row arrangement, while in the row intercropping one or more crops are planted in rows. Growing two or more crops simultaneously in different strips wide enough to permit independent cultivation but narrow enough for the crops to interact ergonomically is considered as strip intercropping. The last intercrop pattern is relay intercropping and it includes growing two or more crops simultaneously during part of the life cycle of each. A second crop is planted after the first crop has reached its reproductive stage but before it is ready for harvest.

Besides spatial arrangement, the intercropping benefits are also dependent on species selection. Thus, cropping systems based on carefully designed species mixtures enable many potential advantages such as forage yield increase, weed control, reduced soil erosion, lower pests and diseases under various conditions. This practice is efficient way of weed suppresion mainly through competition for growing sources, but also an ecological and economical which reduces application of pesticides and their negative impact on the environment.

One of the most used tools for the evaluation of the benefits of intercrops is the Land Equivalent Ratio (LER). LER allows measuring the yield advantage obtained by growing two or more crops or varieties in intercropping compared to growing those crops or varieties solely. When the LER value is higher than 1, the intercrop is more productive than the component crops grown as sole crops, while when the LER is lower than 1, the sole crops are more productive than the intercrop. Therefore, intercropping systems based on carefully designed mixtures could have numerous potential advantages in various conditions in comparison to the intensive systems based on sole crops.

Despite all its advantages, during the last 50 years intercropping significantly decreased from many farming systems due to agricultural intensification (plant breeding, mechanization, fertilizer and pesticide use). Clover/grass mixtures in pastures are still widely used in European agriculture, but arable intercropping (cereals, grain and forage legumes, oil seeds) for food and feed is presently not so common. Re-introducing intercropping in European agriculture to a greater extent should not be reversion to old methodology, but rather considering the usefulness of this old and sustainable cropping practice in a modern, and technology-oriented agriculture.

In Vojvodina Province, north of Serbia, there are initiatives of including legume-based intercropping in the higher extent. Legumes (*Fabaceae* Lindl., syn. *Leguminosae* Juss.) are one of the largest plant families in the world, include annuals and perennials, herbaceous plants, shrubs and trees, and species of temperate and tropical regions. The symbiosis between legumes and *Rhizobium* are of great ecological and agronomic importance, due to their ability to fix large amounts of atmospheric nitrogen (N). Thus, biological nitrogen fixation represents the major source of N input in agricultural soils and due to this symbiosis legumes restore and maintain soil fertility and are significant in the remediation of wastelands, degraded agro-ecosystems and systems that requires nitrogen mineral fertilizers.

The contribution of legumes in intercropping systems is widely acknowledged. Legume-cereal intercropping is regarded as highly relevant in low-N-input systems and organic farming where nitrogen is often a limiting resource for crop growth. It has been shown that intercropping improve soil conservation, is efficient in weed control, reduce pests and diseases and provide better lodging resistance. There are a number of other benefits of legumes in a cropping system such as: reducing greenhouse effect, less potential for environmental degradation, improved soil physical conditions and water relations, improve rotations for management efficiency and biodiversity, increasing soil carbon content, lower energy consumption in agriculture etc.

3.2.1. Establishing perennial legumes in intercropping

In several researches in Serbia the intercropping practice was used in establishing perennial legumes. Perennial forage legumes can be established either in summer/fall or in spring. Since they have a small seed size, perennial legumes are sown shallowly and are especially vulnerable to drought. A spring-sown crop has often a significantly lower yield in the year of establishment than a crop sown in the previous fall. This is partly a result of weeds impact, which is a greater problem in a spring-sown crop. Therefore, difficulty in obtaining an economically significant yield from perennial forage legumes in the year of establishment has forced the farmers to establish these crops with a companion crop. Intercropping perennial legumes with some companion crop is as an effective method of agricultural and especially forage production because it offers more stable and higher yield, increased weed competition, higher protein content, and higher land-use efficiency.

Perennial legumes are traditionally intercropped with cool-season cereals primarily oat and barley even though tend to be too fast growing and therefore too competitive crops in comparison to the perennials. Such companion crops compete with the under sown legumes, reducing their yield and, in some cases, even their persistence. Novel research have shown that annual legumes such as pea and vetches are suitable for intercropping with perennial forage legumes, because they can be harvested quickly and the canopy structure is not dense enough to cause suppressive shading. Because of its short growing season, pea and vetches are suited to be cut together with the first cut of a perennial forage legume in its establishment year, significantly increasing crude protein yield. In those researches pea varieties differ in morphology, primarily in stem length and leaf type was used. The varieties with normal-leaf type with reduced leaflet area, allow a greater amount of light through their canopy as a companion crop than the normal-leafed varieties with large leaflet area. Besides these varieties, especially interesting are the semi-leafless or afila-leafed varieties, with all the leaflets transformed into tendrils. The semi-leafless varieties with short stems could be more adapted for intercropping with perennial forage legumes since the light penetration is more intense, providing better conditions for the initial growth of the legumes. In addition, including pea in intercropping with perennial legumes makes improve forage quality and digestibility, that is, increasing the forage crude protein content and decreasing both neutral (NDF) and acid (ADF) detergent fiber.

At the Experimental Field of Institute of Field and Vegetable Crops, Novi Sad (IFVCNS) several researches was carried out of establishment alfalfa and red clover with different field pea varieties. The pea varieties appeared not to have affects on the establishment of perennials. Following the success in the experiments with establishing named perennial legumes, a series of trials was conducted with sainfoin, established with two pea varieties, namely one normal-leafed and another semi-leafless (Picture 1), sown at the densities of 30, 60, and 90 plants m^{-2} and as sole crop and intercropped with oat, as a traditional companion crop (Picture 2). The sole crop of sainfoin had the lowest five-year average forage dry matter yield in its first cut in the establishment year (2.1 t ha^{-1}), while the significantly highest five-year average forage dry matter yield (6.5 t ha^{-1}) was in oat. The semi-leafless pea variety had higher five-year average forage dry matter yield (5.2 t ha^{-1}) in comparison to the normal-leafed variety (4.9 t ha^{-1}), which is a consequence of a loss of lower leaves in a higher extent in normal-leafed varieties than in the semi-leafless ones, A significantly higher five-year average total forage dry matter yield in the first cut of the establishment year of sainfoin (5.9 t ha^{-1}) in its intercrop with 90 plants m^{-2} of the semi-leafless pea variety. However, it is recommended to make a compromise between high sowing rates, which maximize the total forage dry matter yield, but are too aggressive for perennial legumes, and low sowing rates, which decrease yield and are insufficient to suppress weeds. To avoid too severe competition with the undersown legume, it has also been recommended that the sowing rate of the pea companion crop should be reduced by up to half, as well as to cut the pea companion crop early for forage. The individual contribution of sainfoin in its intercrops with oat and two varieties of pea with different leaf types in its first cut of the establishment year ranged between 0.5 t ha^{-1} when intercropped with 90 plants m^{-2} of the semi-leafless pea variety and 1.2 t ha^{-1} when intercropped with 30 plants m^{-2} of the normal-leafed pea variety.

Picture 3.5. Intercropping of sainfoin and normal-leafed pea (left) and intercropping of sainfoin and semi-leafless pea (right)

Although the highest forage dry matter yield is usually obtained in intercropping with oat as the companion crop, the yield itself is not the only criterion for determining the suitability of pea as the companion crop. The forage coefficient of digestibility in the diet of ruminants should be considered as important. It was reported that the digestibility coefficients of red clover, pea, and oat at the cutting stage are 71%, 79%, and 54%, respectively. In addition, pea has more suitable morphological and biological characteristics, which tend to balance the negative effects it may have as a companion crop in both the establishment year and the first year of full use. In the same trial, the sole crop of sainfoin had the highest weed proportion, while there were differences in weed proportion between two pea varieties. The weed proportion, in the same manner as the red clover proportion, decreases as plant number of the pea companion crop increases. Using an oat as the companion crop may also reduce the number of weeds in the established perennials by up to 50% as compared to the sole crop of the latter.

Picture 3.6. Control treatments - pure stand of sainfoin (left) and intercropping of sainfoin and oat (right)

The five-year average values of the LER of forage dry matter was significantly higher in pea generally (1.03) than in the intercrop of sainfoin with oat (0.80) and thus proved economically justified. On the other hand, the mean value of the LER of forage dry matter for all three sowing densities of the semi-leafless pea variety used for accompanying the established sainfoin (1.13) was significantly higher than that of the normal leafed pea variety (0.92). In this way, the semi-leafless varieties demonstrated their suitability for reliable forage production in comparison to the normal-leafed pea varieties.

3.2.2. Intercropping of annual legumes with other annual crops

In many temperate and humid regions, annual legumes may be intercropped with brassicas (*Brassicaceae* Juss.). The brassicas like rapeseed is a more appropriate companion than barley in the intercropping with pea, resulting in more efficient nitrogen fixation. In legume–brassica intercrops, such as faba bean with rapeseed and common vetch with fodder cabbage, root architecture of the companions is complementary reducing the effect of competition. Root complementarities are more important than nitrogen transfer between the legume and the brassica for enhancing intercrop performance. With brassicas included there is a possibility for triple intercrops, comprising annual legumes, cereals, and brassicas such as pea, wheat, and rapeseed, which are more efficient in weeds suppression, simultaneously producing higher yields of both dry matter of forage and grain, confirmed by LER values higher than 1.2. The intercrops of both fall- and spring-sown annual legumes, such as pea, vetches, and grass pea, with brassicas, namely rapeseed, fodder kale, and white mustard, demonstrated LER values higher than 1 in both forage dry matter and forage dry matter crude protein yields. Certain tropical annual legumes with large leaves such as lablab bean provide increased yields and desirable LER values when intercropped with leafy vegetables such as lettuce. The results of the trials carried out in southern France with intercropping soybean with sunflower confirm that it is particularly suited to low nitrogen input systems due to the complementary use of nitrogen sources by these two species.

3.2.3. Intercropping of annual legumes with other annual legumes

The growing two or more annual legumes in intercropping is not so present in the published resources. However, in the available papers it was shown that the mutual intercrops of annual legumes are mostly beneficial, at least for one of the components. For example, white lupin may use the forms of phosphorus that accompanying soybean cannot. Similarly, if intercropping soybean with pigeon pea is combined with subsoiling, it may mitigate the effects of droughts of certain intensity. Most legumes release carboxylic acids that dissolve phosphate ions from bound forms such as calcium and iron phosphates that are otherwise unavailable to plants and immobile in the soil. The process is to an extent self-regulating: the lower the phosphorus concentration in the soil, the more acid is released. The same principle may work in two-legume mixtures, where one component is more phosphorus-efficient than the other. On the other hand, in the intercrop system of pigeon pea and soybean there may be a competition for available nitrogen resulting in the depression of growth of the soybean.

During the past decade, the Institute of Field and Vegetable Crops and the Faculty of Agriculture of the University of Novi Sad have carried out a concerted research aimed at assessing the possibility of mutual annual legume intercropping for forage and grain production. The primary goal of this complex study was to find out if any of combinations may mean an increase in forage and grain yield, with subsequent research aimed at forage and grain quality, tolerance to abiotic and biotic stress and other-agronomic and physiological aspects. LER was determined for each combination s a main indicator of the reliability and profitability. One of the main conclusions of the preliminary testing of hundred of accessions and varieties are: species with long and lodging stems (i.e. vetches) easily control weeds in pure stands but suffer from forage losses; crops with good standing ability (i.e. faba bean) usually are infested by weeds in pure stands and require chemical control; intercropping annual legumes gives significant advantage to one or both components.

The results of this examination led to the establishment of four basic principles essential for a successful intercropping of two annual forage legumes:

- the same time of sowing;
- the similar growing habit;
- the similar time of maturing for cutting (for forage production) or harvest (for grain production); and
- one component has good standing ability (supporting crop) and another is susceptible to lodging (supported crop).

Following these main principles, further analyses were divided on three main groups of annual legume crops:

- fall- and spring-sown “tall” cool-season annual legume crops;
- fall- and spring-sown “short” cool-season annual legume crops; and
- early and late-maturing warm-season annual legume crops.

The “tall” annual legume crops are characterized with long stem length. Within both the fall- and spring-sown subgroups, faba bean and white lupin played the role of supporting crop, while the supported crops were pea, common vetch, Hungarian vetch, hairy vetch, and grass pea. Annual legumes with good standing ability, such as faba bean or white lupin, are usually sown in wide rows and thus provide favorable conditions for weed development. On the contrary, annual legumes, such as pea, many vetches, or grass pea, suppress weeds but are extremely prone to lodging, even in the optimum stages for cutting, with heavy losses or lower leaves and reduced- and less-quality forage and grain yields. Intercropping these two types of "tall" cool-season legumes may be beneficial for both.

The annual forage legume crops within the "short" group have short stem length, often with determinate growth. The fall-sown crops comprised semi-leafless pea as supporting crop, and normal-leafed pea, bitter vetch, and lentil as supported crops, while the spring-sown crops are semi-leafless pea and fenugreek as the supporting crop, while normal-leafed pea, lentil, chickpea, and barrel medic played a role of supported crops. The basic principles are also applied in this model of intercropping. Pure stand of fenugreek may suffer from certain degree of weed infestation, even though act as a biofumigant against most weeds in cool season annual field crops. This crop may be a support for the short-stemmed annual legumes prone to lodging and losing lower leaves, such as lentil. This case, where an annual crop with a bioherbicide properties is involved, is mainly aimed at both fighting the weeds in the intercrop with other annual legume and preserving its photosynthetic activity and both forage and yield of its supporting component.

If intercropped with each other, semi-leafless and normal-leafed peas may profit from each other: semi-leafless pea provides improved standing ability of the intercrop, while normal-leafed pea fills the available space within the stand and contributes to better utilization of sunlight, at the same time reducing weed growth. This combination enables benefits for both intercrops having in mind that semi-leafless pea has significantly improved standing ability and profits from sunlight penetrating the whole stand, but also offers more favorable conditions for weed development and normal-leafed pea controls weeds in an easier manner, but is prone to lodging at early stages and is danger of losing lower leaves and disease infestation.

In the trials with warm-season annual forage legumes a spring sowing was performed. The combinations that were analyzed included the early maturing group soybean (00 maturity group) was supporting crop, while several *Vigna* species, namely mung bean, adzuki bean and black gram were supported crops. Soybean belonging to the late-maturing group (I maturity group) and pigeon pea was used as supporting crops, while cowpea and lablab bean played the role of supported crops. Regardless of its maturity group, a soybean crop provides weeds with favorable conditions for rapid development and thus regularly requires intensive mechanical or chemical weed control. On the other hand, the *Vigna* species (notably cowpea and lablab) are exceptionally prone to lodging and by forming a mighty and creeping cover of stems and leaves are able to almost eliminate any weed species, but may also loose lower leaves and cause serious difficulties during the cutting. When intercropped, soybean may carry cowpea or lablab stems and thus assist in preserving its leaves, as well as benefit from significantly decreased weed infestation.

It should be emphasized that the most adequate proportion of both components in intercrops is half of the pure sowing rate (50%:50%) of each intercrop and this measure is usually applied in order to avoid unnecessarily expensive and economically unjustified sowing, which is extremely unpopular among the farmers worldwide.

3.2.3.1. Intercropping "tall" cool-season annual legumes with each other

The series of trials carried out from the fall 2008 to the spring 2013, at the Experimental Field of IFVCNS includes following species: faba bean, white lupin, pea, common, hairy and Hungarian vetch and grass pea as fall sowing crops and faba bean, white lupin, pea, common and Narbonne vetch, grass pea and red vetchling as spring sowing crops This type of mixtures demonstrated high potential for both forage dry matter and grain yields, as well as for a reliable production.

Among the fall-sown annual legumes the highest forage dry matter yield as sole crops have hairy vetch and pea (11.3 t ha^{-1} and 10.8 t ha^{-1} respectively). Spring-sown pea also has a high potential for forage production, with 10.4 t ha^{-1} of forage dry matter. On contrary, the lowest forage dry matter yield of the fall-sown annual legumes grown as sole crops is in Hungarian vetch (7.3 t ha^{-1}) and in Narbonne vetch (7.7 t ha^{-1}) in the spring-sown group. Intercrops of faba bean with pea and common vetch in both terms of sowing have the highest total forage dry matter yield, which ranges from 11.2 t ha^{-1} to 12.5 t ha^{-1}. Faba bean and white lupin have lower contribution in the total forage dry matter yield if intercropped with hairy vetch or grass pea as the supported annual legumes with rather abundant aboveground biomass. According to LER values economically reliable were the intercrops of both fall- and spring-sown faba bean and white lupin with pea and vetches, those with Hungarian vetch, with white lupin and Narbonne vetch, with faba bean and white lupin (Picture 3).

The spring-sown "tall" annual legumes with highest potential for grain production if grown as sole crops in temperate regions were white lupin, faba bean, grass pea, and pea (4.6, 4.2, 4.0, and 3.9 t ha^{-1}, respectively). Species like Narbonne vetch or red vetchling, usually have much lower grain yields, greatly because of lack of achievements in breeding and developing varieties specifically for

Picture 3.7. Intercropping of winter faba bean with Hungarian vetch

grain production. The average five-year grain yield ranged from 3.5 t ha^{-1} in the intercrop of white lupin with common vetch to 5.2 t ha^{-1} in the intercrop of white lupin with grass pea. Both faba bean and white lupin are the most dominant and productive in the intercrop with Narbonne vetch. Among the supported intercropping compo-

Picture 3.8. Intercropping of spring white lupin with spring grass pea

nents, grass pea produces the highest individual contribution to the total grain yield (2.7 t ha^{-1}), while Narbonne vetch has the lowest one (0.8 t ha^{-1}). This is mainly due to the fact that grass pea produces abundant aboveground biomass and great number of pods and grains per plant. In terms of LER indicator, the most reliable intercrops of faba bean from an economical viewpoint were those with common and Narbonne vetches (both 1.22), while the same in the case of white lupin is when intercropped with grass pea (1.23) (Picture 4).

3.2.3.2. Intercropping "short" cool-season annual legumes with each other

The trials conducted from the fall 2008 to the spring 2013 at the Experimental Field of IFVCNS at Rimski Sancevi, were included numerous combinations of both intercrops and varietal mixtures of "short" cool-season annual legumes - semi-leafless pea, bitter vetch, lentil, barrel medic, normal-leafed pea variety and fenugreek).

In a trial comprising a semi-leafless and normal-leafed variety, the average forage dry matter yield in sole crops was statistically significant. It ranged between 5.5 t ha^{-1} in the spring-sown semi-leafless in 2008-2009 and 8.0 t ha^{-1} in the fall-sown normal-leafed in 2009-2010. In 2008-2009, forage dry matter yield in the fall-sown intercrop (7.7 t ha^{-1}) was significantly higher compared to the forage dry matter yield in the spring-sown intercrop (6.4 t ha^{-1}). In 2009-2010, the fall-sown intercrop was significantly more productive (8.4 t ha^{-1}) than the spring sown intercrop (6.5 t ha^{-1}). The LER values were economically justified in both fall- and spring-sown intercrops although the fall-sown was significantly productive (1.13) than the spring-sown intercrop mixtures (1.03).

The semi-leafless variety had significantly higher yield than the normal-leafed variety. In all intercrops, the semi-leafless variety had significantly higher proportion in the total grain yield than the normal-leafed one, ranging from 3.2 t ha^{-1} to 1.2 t ha^{-1} at 75%:25% and from 2.3 t ha^{-1} to 1.5 t ha^{-1} at 50%:50% ratio. The most economically reliable combination were in the intercrops of 75% of the semi-leafless and 25% of the normal-leafed varieties, with LER 1.17, 1.27, and 1.14, respectively.

A five-year average grain yield of fall-sown semi-leafless pea was 5.2 t ha^{-1} and confirms its prominent production potential. On contrary, annual legumes such as fenugreek and barrel medic had the lowest grain yield, 0.98 and 0.87 t ha^{-1}, respectively. The total grain yield was the lowest one (0.9 t ha^{-1}) was in the intercrop of spring-sown fenugreek and barrel medic and the highest in the intercrop of fall-sown semi-leafless pea with bitter vetch (4.9 t ha^{-1}). The significant differences were obtained in yield of the intercrop components. The highest individual contribution of any intercrop component in the total grain yield was in fall-sown semi-leafless pea (2.8 t ha^{-1}) with bitter vetch, while the lowest one was in barrel medic (0.4 t ha^{-1}) with fenugreek. A spring-sown lentil had almost a double lower five-year average grain yield when intercropped with fenugreek than the fall-sown one intercropped with semi-leafless pea, probably as a potential allelopathic reaction by fenugreek. The most reliable intercrops were those of semi-leafless pea with bitter vetch and fenugreek with normal-leafed pea, with LER values of 1.15 in both cases.

3.2.3.3. Intercropping warm-season annual legumes with each other

Soybean, pigeon pea, mung bean and lablab bean as warm-season annual legumes were included in the trials evaluating its potential for forage yield and intercropping for both forage and grain production.

The average green forage yields in sole crops ranged between 14.5 t ha^{-1} in pigeon pea and 42.0 t ha^{-1} in the soybean from the 00 maturity group and 42.8 t ha^{-1} in the soybean from the I maturity group. In intercropping systems the average total green forage yield ranged from 26.8 t ha^{-1} in the intercrop of lablab bean and pigeon pea to 37.9 and 38.3 t ha^{-1} in intercrops of mung bean with the soybean from the 00 maturity group and lablab bean with the soybean from the I maturity group. The average forage dry matter yields in sole crops ranged from 4.4 t ha^{-1} in pigeon pea to 12.2 t ha^{-1} in the soybean from I maturity group and from 7.7 t ha^{-1} in the intercrop of lablab bean and pigeon pea to 10.9 t ha^{-1} in the intercrop of lablab bean and the soybean from I maturity group. In these trials mung bean confirmed its potential for the forage dry matter production in temperate European environments. The LER for green forage yield varied from 1.01 in the intercrop of mung bean and soybean 00 to 1.12 in the intercrop of lablab bean and pigeon pea. The highest LER values for forage dry matter yield were 1.10 in the intercrop of lablab bean and pigeon pea, while the lowest one was in the intercrop of soybean 00 and mung bean (0.99). The latest trials in temperate region such as Serbia aimed at intercropping warm-season annual legumes for grain production. Those trials have shown that LER values are higher than 1 and with a high potential for further analysis.

3.2.4. Conclusions

Intercropping is a promising and significant growing practice especially in sustainable and organic agriculture. The first assessments in use of the potential of both forms of mutual legume intercropping for forage yield and weed suppression in the case of establishing perennial forage legumes with annual legumes and for both forage and grain yield in the case of intercropping annual legumes with each other have been done. It has been demonstrated that perennial forage legumes such as alfalfa, red clover and sainfoin if established together with an annual legume, such as semi-leafless pea, may have different benefits - the annual legume has an ability to fight the weeds in a young perennial forage legume stand and together contribute to the forage dry matter yield in its first cut.

It has also been shown that intercropping of two annual legumes produces high and economically reliable forage and grain yields. In the end, the first hints of a possibility for breeding annual legume varieties specifically for intercropping either with perennial forage legumes or other annual legumes for forage and grain production have been given. Further research should be based on the analysis of different intercropping combinations on the quality parameters, with emphasis on crude protein content and digestibility.

Table 3.1. The list of species and their latin names as they were mentioned in the text

Common name	Latin name	Common name	Latin name
Pea	*Pisum sativum* L.	Faba bean	*Vicia faba* L.
Oat	*Avena sativa* L.	Common vetch	*Vicia sativa* L.
Barley	*Hordeum vulgare* L.	Hungarian vetch	*Vicia pannonica* Crantz.
Alfalfa	*Medicago sativa* L.	Hairy vetch	*Vicia villosa* Roth
Red clover	*Trifolium pratense* L.	Bitter vetch	*Vicia ervilia* (L.) Willd.
Sainfoin	*Onobrychis viciifolia* Scop.	Lentil	*Lens culinaris* Medik.
Rapeseed	*Brassica napus* L.	Fenugreek	*Trigonella foenum-graecum* L.
Grass pea	*Lathyrus sativus* L.	Chickpea	*Cicer arietinum* L.
Fodder kale	*Brassica oleracea* L. var. *viridis* L.	Barrel medic	*Medicago truncatula* Gaertn.
White mustard	*Sinapis alba* L.	Mung bean	*Vigna radiate* (L.) R. Wilczek
Lablab bean	*Lablab purpureus* (L.) Sweet	Adzuki bean	*Vigna angularis* (Willd.) Ohwi & H. Ohashi
Lettuce	*Lactuca sativa* L.	Black gram	*Vigna mungo* (L.) Hepper
Soybean	*Glycine max* (L.) Merr.	Cowpea	*Vigna unguiculata* (L.) Walp.
Sunflower	*Helianthus annuus* L.	Narbonne vetch	*Vicia narbonensis* L.
White lupin	*Lupinus albus* L.	Red vetchling	*Lathyrus cicera* L.
Pigeon pea	*Cajanus cajan* (L.) Millsp.		

Part 4 – Appendix

4. An overview of available data bases useful in agriculture

4.1. FAO – soils

FAO - Food and agriculture data
http://www.fao.org/faostat/en/#home

FAOSTAT provides free access to food and agriculture data for over 245 countries and territories and covers all FAO regional groupings. Within a wide range of top topics like Production (crops, crops processed, live animals, etc.), Food Balance etc. the most relevant top topic is Agri-Environmental Indicators including- Soil- Water- Land Use- Land Cover

FAO SOILS PORTAL
http://www.fao.org/soils-portal/en/
Description of content
The FAO SOILS PORTAL is designed as a source of soil information and knowledge on the different components and aspects of soils and the value and importance of this vital and finite resource for policy makers, development planners, soil science experts, agricultural extension workers, academic/institutions and other practitioners.

“Soil-Survey” is an excellent starting point for targeted recherché.
http://www.fao.org/soils-portal/soil-survey/en/

Example – how to find soil information from AUSTRIA
The following example shows the way from this portal to comprehensive soil information of Austria. The detailed steps are:

- Soil properties
- Soil classification
- Sampling and laboratory techniques
- **FOLLOW Soil Maps and Databases**

http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/en/

Legacy maps and databases refer to data and maps compiled using field surveys backed up by remote sensing and other environmental data, expert opinion and laboratory analysis. The bulk of soil information was collected in this way. The technological advances in remote sensing, computers, terrain analysis, geostatistics, GIS data integration, and instrumentation has made it possible to achieve unprecedented reliability and utility in digital soil maps. There is an increasing amount of digital data available on the Internet or as large datasets on CD-ROM, from straight digital conversions of paper maps and databases to direct-to-digital products. Unfortunately, there is also a lot of digital data that is not easily or freely available.

- FAO/UNESCO Soil Map of the World
- Harmonized world soil database v1.2
- Other Global Soil Maps and Databases
- **FOLLOW Regional and National Soil Maps and Databases**
- Soil Profile Databases
- FAO Soil Legacy Maps
- Soil Legacy Reports

http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/regional-and-national-soil-maps-and-databases/en/

Within the continental menu:

- Africa
- Asia
- Australia, New-Zealand and Pacific Isles
- **FOLLOW Europe**
- North America
- South, Central America and Caribbean
- Pluri-continental Coverage

http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/regional-and-national-soil-maps-and-databases/en/

Within the EUROPE menu:

Europe

- Contact National Soil Information Centers

Regional Soil Maps and Databases

- Soil Atlas of Europe
- The European Soil Database (ESDB)
- SOVEUR at ISRIC_World Soil Centre

National Soil Maps

- European Digital Archive on Soil Maps of the World
- **FOLLOW Austria**
- France
- Germany

- Israel
- Lithuania
- Russia
- Switzerland
- United Kingdom

LANDED!

Bodeninformationssystem BORIS! AUSTRIAN SOIL INFORMATION SYSTEM

http://www.umweltbundesamt.at/umweltschutz/boden/boris

BORIS description

The content on this site is only in GERMAN language; however there follows a translation into ENGLISH about the skills and retrieval methods of the system.

Soil information in Austria - centrally managed and available online. The data portal gives access to the BORIS data, data retrieval and data presentation tools. BORIS data is harmonized according to the data key "Bodenkunde" and compliant in accordance with the specifications of the INSPIRE guideline.

BORIS informs about the condition of Austrian soils. The Federal Environment Agency provides soil data of the federal states and the federal government in a comparable and quality-tested form online.

The data in BORIS are prepared using a code key specially developed by Boden experts ("Bodenkunde data key"). This allows testing for methodological differences in e.g. Survey and measurement methods and the assignment of data according to clearly defined schemes.

BORIS currently contains more than 1.5 million data records from more than 10,000 locations in Austria.

The data provide information about

- Locations and their characteristics (e.g. soil type, geology, water balance, vegetation, use ...)
- Soil characteristics (soil horizon characteristics, sampling ...)
- chemical, physical and microbiological analyzes:
  - Pollutants such as heavy metals (eg mercury, Hg [mg/kg]) or organic pollutants (PAHs, PCBs, pesticides ...)
  - e.g. Soil type, contents of clay silt, sand, soil carbon ...

Overall, a spectrum of almost 600 pedological parameters is available - with varying availability depending on the examination.

BORIS data offer quality by

- the existence in comparable form (Austria-wide)

- consistency and plausibility check of the data
- simultaneous availability of data from different studies in a consistent format. This facilitates the further processing with statistics or geographical information systems (GIS)

The BORIS Data Portal offers:

- individual data selection and data representation via WebGIS as well as various map layers and base maps
- individual data selection according to examinations and soil information
- Data output in EXCEL and reports
- Creation of data overviews and data availability
- Digital data key Soil science
- online data ordering („Datastore")
- Data provision according to the specifications of the INSPIRE Directive

The following datasets are integrated in BORIS:

- the area-wide soil condition inventories of the federal states
- the comprehensive Austrian Forest Soil State Inventory, Repeat sampling of the Level II areas as part of BioSoil
- the Austria-wide Radio Cesium survey
- Data from more than 30 other local investigations on specific issues, such as Industrial sites or metropolitan areas

The information system is constantly being expanded with the latest ground data and developed technically.

Data query

The BORIS data portal makes Austria-wide soil data accessible across federal states in a Web-GIS application (Disy Cadenza). Location and horizon / sample properties and measured values (availability *) of the sampling points can be easily selected according to soil analyzes and soil parameters, displayed in tables or geographically and output as Excel spreadsheets or reports.

Various maps, such as the ÖK, the soil groups in Austria, forest growth areas or the monitoring network of the aquifers can be selected as background layer. This allows individual data selection and adaptation of the presentation depending on the problem.

Access is via a standard web browser, no further additional installations are required. https://wasser.umweltbundesamt.at/cadenza/pages/map/default/index.xhtml

4.2. EURISCO – Finding seeds for the future

https://eurisco.ipk-gatersleben.de

EURISCO is a web-based catalogue that provides information about ex situ plant collections maintained in Europe. EURISCO is based on a European network of ex situ National Inventories (NIs) that makes the European plant genetic resources data available everywhere in the world. The EURISCO Web Catalogue automatically receives data from the NIs through country National Focal Points (NFPs).

The EURISCO Catalogue contains passport data about 1.8 million samples of crop diversity representing more than 6,200 genera and more than 41,600 species (genus-species combinations including synonyms and spelling variants) from 43 countries (updated January 2016).

These samples of crop diversity represent more than half of the ex situ accessions maintained in Europe and roughly 16% of total worldwide holdings. EURISCO is a one-stop shop window using international standards for information on ex situ plant collections that enables users to search and access information on food crops, forages, wild-and-weedy species, including cultivars, landraces, farmers' varieties, breeding lines, genetic stocks and research material.

Following the mandate and guidance given by the ECPGR (European Cooperative Programme for Plant Genetic Resources) Steering Committee, EURISCO is hosted at and maintained by IPK (Leibniz Institute of Plant Genetics and Crop Plant Research) Gatersleben on behalf of Bioversity International, which acts as the legal entity of the Secretariat of the European Cooperative Programme for Plant Genetic Resources (ECPGR), in collaboration with and on behalf of the National Focal Points for the National Inventories.

EURISCO is working with NFPs to improve the search mechanisms, data and metadata standards, web services and other necessary components of an Internet-based information infrastructure for ex situ plant genetic resources. EURISCO makes data from the NIs available to users around the world. These data are made available according to the existing data policy - legal notice and terms of use.

Here are some examples of the National Focal Points:

Austria

Mr Paul Freudenthaler, AGES Austrian Agency for Health and Food Safety, Department for Plant Genetic Resources

Wieningerstrasse 8, 4020, Linz, Austria

http://www.genbank.at

Bosnia and Herzegovina

Ms Marina Antić, Genetic Resources Institute, University of Banjaluka

Univerzitetski grad, Bulevar vojvode Petra Bojovi¿a 1A, 78000, Banjaluka, Bosnia and Herzegovina

Croatia

Ms Mirta Culek,

Croatian Centre for Agriculture, Food and Rural Affairs,

Institute for Seed and Seedlings

Usorska 19, Brijest, 31000, Osijek, Croatia

http://www.zsr.hr

Italy

Ms Maria Antonietta Palombi, CRA -FRU Fruit Tree Research Centre

Via Fioranello, 52, 00134, Roma, Italy

Serbia

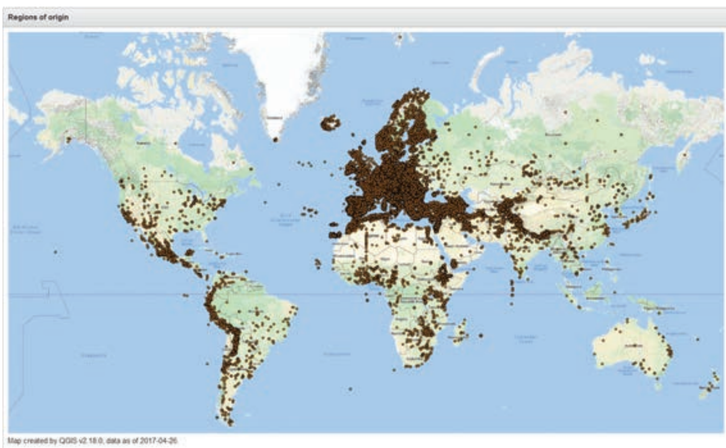
Ms Milena Savić Ivanov, Ministry of Agriculture and Environmental Protection,

Directorate for National Reference Laboratories, Gene Bank Department

Batajnicki drun part 7, No 10, 11080, Belgrade - Zemun, Serbia

http://www.minpolj.gov.rs

Next Figure shows the remarkable EURISCO map “regions of origins”.



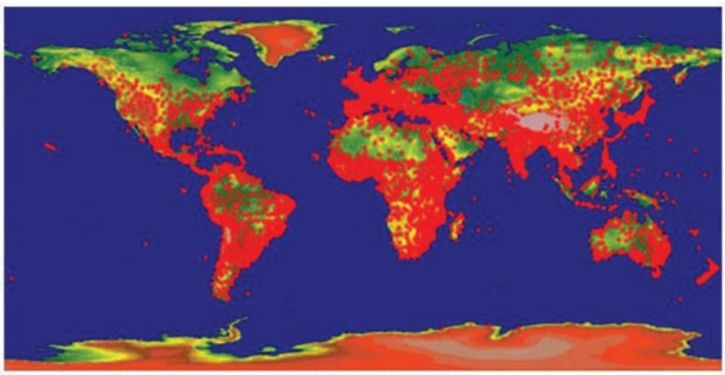
4.3. CLIMWAT

http://www.fao.org/land-water/databases-and-software/climwat-for-cropwat/en/

CLIMWAT is a climatic database to be used in combination with the computer program CROPWAT and allows the calculation of crop water requirements, irrigation supply and irrigation scheduling for various crops for a range of climatological stations worldwide.

CLIMWAT 2.0 for CROPWAT is a joint publication of the Water Development and Management Unit and the Climate Change and Bioenergy Unit of FAO. CLIMWAT 2.0 offers observed agroclimatic data of over 5000 stations worldwide.

Next Figure shows the global distribution of available weather stations.



Location of stations included in CLIMWAT 2.0

CLIMWAT provides long-term monthly mean values of seven climatic parameters, namely:

- Mean daily maximum temperature in °C
- Mean daily minimum temperature in °C
- Mean relative humidity in %
- Mean wind speed in km/day
- Mean sunshine hours per day
- Mean solar radiation in MJ/m2/day
- Monthly rainfall in mm/month
- Monthly effective rainfall in mm/month
- Reference evapotranspiration calculated with the Penman-Monteith method in mm/day.

The data can be extracted for a single or multiple stations in the format suitable for their use in CROPWAT. Two files are created for each selected station. The first file contains long-term monthly rainfall data [mm/month]. Additionally, effective rainfall is also included calculated and included in the same file. The second file consists of long-term monthly averages for the seven climatic parameters, mentioned above. This file also contains the coordinates and altitude of the location.

All station information is drawn from the database of The Agromet Group of FAO.

All variables, except potential evapotranspiration, are direct observations or conversions of observations. Original data coming from a large number of meteorological stations as included in CLIMWAT, could not be uniform. For example, humidity and radiation can be expressed through different variables. With respect to humidity, data can be provided as relative humidity, dew point temperature or water vapour pressure. These three variables can be uniquely converted into each other if the mean temperature is known. However, if humidity is measured and provided in more than one of these variables, the actual numbers would not necessarily be in line. In this case it is necessary to decide which variable to use. When compiling CLIMWAT, it was decided to use water vapour pressure as a core variable and only where it is not available, use dew point temperature and relative humidity. However, there is a risk that the provided value of vapour pressure is higher than the one that is possible to obtain, given the mean temperature. The original databases were crosschecked for this possible inconsistency and one of the other variables was used in the few cases where it occurred.

The same problem arises with radiation. Instead of the solar energy flux at the surface often only sunshine hours or sunshine fraction are recorded, both of which though can be converted to radiation. In order to calculate evapotranspiration using the Penman-Monteith method, both radiation and sunshine fraction are necessary. To keep both these values in agreement the observed radiation was used as base variable and the sunshine fraction was estimated from it. When only the sunshine fraction (or hours) has been observed it was used to estimate radiation. If both (fraction and radiation) are observed radiation was preferred.

As a result, the provided relative humidity and sunshine hours are often deduced from observations of vapour pressure and radiation, even if the former are observed. The procedure, however, ensures that the different expressions are coherent.

In compiling the data, an effort was made to cover the period 1971 - 2000, but when data for this period were not available, any recent series that ends after 1975 and that has at least 15 years of data have been included. Some of the series are „broken", but they nevertheless have at least 15 years of data (e.g. 1961-70 and 1992-2000).

We prepared the dataset and the extraction software with great care and made every effort to provide reliable data. However, we cannot guarantee that all the observations that went into the procedure are free of errors.

All station information is drawn from the database of The Agromet Group of FAO.

4.4. CARPATCLIM – Climate of the Carpathian Region

http://www.carpatclim-eu.org/pages/home/

The CARPATCLIM project was designed to improve the basis of climate data in the Carpathian Region for applied regional climatological studies such as a Climate Atlas and/or drought monitoring, to investigate the fine temporal and spatial structure of the climate in the Carpathian Mountains and the Carpathian basin with unified methods. Therefore, a freely available, high resolution gridded database has been produced for the Larger Carpathian Region (LCR).

Homogenized, quality proofed data is available with:

Timeframe:

- 1961-2010

Spatial range:

- Climatological grids cover the area between latitudes 44°N and 50°N, and longitudes 17°E and 27°E

Temporal resolution:

- 1 day

Spatial resolution:

- 0.1˚ x 0.1˚

The data can be accessed via the web. The digital Atlas provides a database of gridded maps (meteorological variables and derived indicators) of the whole Carpathian Region with the purpose of view and download. Visualisation and download can be limited to selectable specific years, months or days of the year, and selected spatial regions/countries.

Meteorological variables:

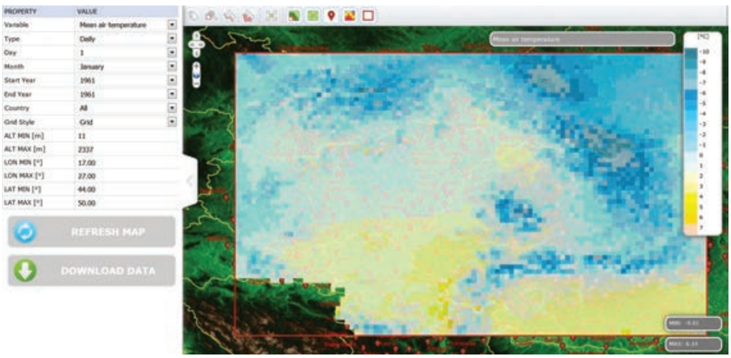
- Mean/Max/Min Air Temperature
- Precipitation
- Sunshine Duration
- Relative humidity
- Surface air pressure
- Surface vapour pressure
- Cloud cover
- Sunshine duration
- Global radiation
- Wind speed (mean, 2m and 10m)
- Wind direction

- Maximum wind speed (10m)
- Snow depth (cm)
- Snow water equivalent (mm)

More than 30 climate indicators and indices such as:

- Number of severe cold days
- Number of frost days
- Number of hot days
- Growing season length
- Potential evapotranspiration
- SPI 3/6/12
- Aridity index
- Moisture index
- and more …

The following Figure shows a screenshot of the web map



The following organizations participated in the project:

- Hungarian Meteorological Service (leading organisation)
- Central Institute for Meteorology and Geodynamics, Austria
- Meteorological and Hydrological Service of Croatia
- Czech Hydrometeorological Institute
- Institute of Meteorology and Water Management
- National Research Institute, Poland
- National Institute for Research and Development in Environmental Protection of Romania
- Republic Hydrometeorological Service of Serbia
- Slovak Hydrometeorological Institute
- Ukrainian Research Hydrometeorological Institute
- Szent Istvan University, Hungary

4.5. Phenological databases

After a certain decline in 1980s and 1990s phenology have undergone a renaissance in recent decades. For example, phenological observations are going on in almost all European countries (Nekovar et al., 2008). Phenological activities, previously organized exclusively at national level, have entered into wide international cooperation in Europe through a program COST725 in 2004 which succeeded to establish, in practical terms, a European phenological database. International Society of Biometeorology established the Commission for Phenology in order to harmonize the methods of observation. Further databases are organized either on wider regional (Germany) or national levels (the USA, Australia). These databases are freely accessible and support and promote the research in climatology and environmental sciences. The example of such databases come from Europe and the USA.

4.5.1. Pan European Phenological database (PEP725)

http://www.pep725.eu/

The Pan European Phenology (PEP) project is a European infrastructure to promote and facilitate phenological research, education, and environmental monitoring. The main objective is to maintain and develop a Pan European Phenological database (PEP725) with an open, unrestricted data access for science and education. PEP725 is the successor of the database developed through the COST action 725 "Establishing a European phenological data platform for climatological applications". So far, 32 European meteorological services and project partners from across Europe have joined and supplied data collected by volunteers from 1868 to the present for the PEP725 database. The database presently holds almost 12 million records, about 46 growing stages and 265 plant species (including cultivars).

Next Figure shows the PEP725 project members, for links to members use the link above.

Further partners see next Figure:

To submit actual/ historical phenological observations to the Pan European Phenology Database is welcome. Providing this information is necessary in the desired and in detail described file format.

In 2017, the database structure was completely renewed.

Metadata station information includes:

header	description
s_id	PEP725 station id, will be assigned at the first submission
nat_id	national station number
lon	longitude in decimal degrees [WGS84]
lat	latitude in decimal degrees [WGS84]
alt	altitude in [m] asl
name	name of station

Contact information:

header	description

provider_org	provider organization, for example ZAMG
provider_name	provider- contact person name
provider_email	actual contact address (e-mail) of provider
provider_web	link to the national phenological web site [if existing]

The following diagram shows an example of plotting PEP725 data for Zea Mais, station Obersiebenbrunn in Austria.

4.5.2. The plant phenological online database (PPODB)

www.ppodb.de

PPODB is an online database that provides unrestricted and free access to over 16 million plant phenological observations from over 8,000 stations in Central Europe between the years 1880 and 2009.

Unique features are:

(1) a flexible and unrestricted access to a full-fledged database, allowing for a wide range of individual queries and data retrieval,

(2) historical data for Germany before 1951 ranging back to 1880, and

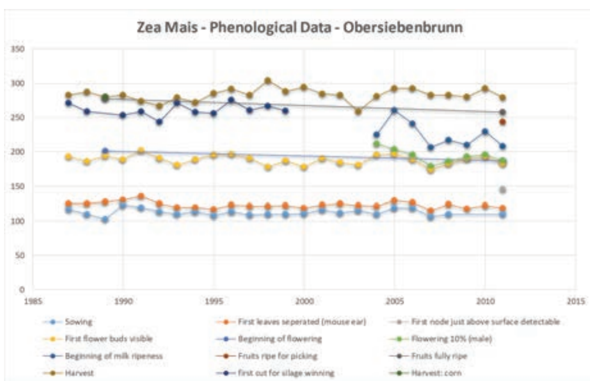
(3) more than 480 curated long-term time series covering more than 100 years for individual phenological phases and plants combined over Natural Regions in Germany.

Time series for single stations or Natural Regions can be accessed through a user-friendly graphical geo-referenced interface.

Data Sources

The PPODB comprises three main data sources:

- **DWD** phenological observations collected by the Deutscher Wetterdienst (German meteorological service, DWD) from 1951 to



2009. This data is referred to as '**DWD**'-data and tables containing this data are named with the prefix 'DWD'.

- **HPDP** the historical phenological database (**HPDB**) provided by the DWD, which is a collection of phenological observations from Central Europe, mainly Germany, covering the years 1880 until 1941 compiled from various sources. This data is referred to as 'HPDB'-data and tables containing this data are named with the prefix 'HPDB'.

- **HIS** To supplement the data for the time before 1951 and to fill the gap between 1941 and 1951 we digitalized phenological data that were available only in printed form. These data were collected by the volunteer network of the precursor of the DWD, the Deutscher Reichswetterdienst, and were published after world war II (Schnelle and Witterstein, 1952; Schnelle and Witterstein, 1964). These observations cover the years 1922 until 1944. Additionally, we digitalized phenological data that were published between 1951 and 1961 in the meteorological yearbooks of the DWD (DWD, 1951; DWD, 1953; DWD, 1960; DWD, 1961). All these historical data were stored in yet another historical phenological database (**HIS**), which for the first time is made publicly available. Only the meteorological yearbooks of the former US-Zone in Germany covered the whole time span from 1945 until 1951, whereas the meteorological yearbooks of the other occupied zones started publishing later, e.g. the British-Zone started 1949. Thus, continuous time series for the whole period from 1880 until 1999 could only be found for southern Germany. This data is referred to as 'HIS'-data and tables containing this data are named with the prefix 'HIS'.

Plants and phases available on PPODB:

- Agricultural plants and phases
- Fruit trees and bushes (orchard) and phases
- Wild growing plants, forest and ornamental woody plants and phases
- Vines

PPODB Data policy

The data stored in the DWD and HPDB database generally underly the data policy of the DWD. Access to the phenological data from the DWD is unrestricted and free of charge according to the conditions of data usage and policies of the DWD.

The data stored the HIS database as well as derived tables for the combined time series are made available under the Open Database License. Any rights in individual contents of the database are licensed under the Database Contents License. Basically you are free to use, share, modify the data, as long as you keep the resulting data equally open and redistribute under the same license. For more details see here.

4.5.3. USA National Phenology Network (USANPN)

www.usanpn.org

Phenology Observation Portal related to USNPN contains customized datasets of observational data from the National Phenology Database, which includes phenology data collected via the Nature's Notebook phenology program (2009-present for the United States), and additional integrated datasets, such as historical lilac and honeysuckle data (1955-present). Filters are available to specify dates, regions, species and phenophases of interest.

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