Monitoring drought affected crop yields based on ERS-scatterometer data

Exploration of possibilities to integrate ERS-scatterometer derived soil moisture into the CGMS crop model for a Russian-Ukrainian study area.

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ABSTRACT

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In this study the possibilities to integrate ERS-scatterometer derived soil moisture into CGMS are explored. This remote sensed soil moisture is used to calculate drought stress in grains of barley for a Russian-Ukrainian study area. The results are compared with drought stress based on the rainfall driven water balance and with regional yields statistics of barley. The use of ERS-scatterometer in CGMS seems promising especially when additional input date like sowing dates and crop parameters are improved and conversions of ERS-scatterometer data into soil moisture are more specified for different soils and seasonal variations.

Keywords: Agronomy, remote sensing, soil water, water limited, yield condition, WOFOST

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Preface

The project described in this report is within the framework of a larger project called 'Yield Condition Service Demonstrators based on the ERS-scatterometer' also called SCATYIELD. The SCATYIELD project was funded by the Data User Programme of the European Space Agency (ESA). Besides ALTERRA (former SC-DLO-Winand Staring Centre) the following partners were involved in this larger project:

- NEO Netherlands Geomatics & Earth Observation B.V, Netherlands;
- Institute for Land & Water Management (ILWM), Catholic University Leuven, Belgium;
- Institute for Photogrammetry and Remote Sensing (IPRS), Technical University Wien, Austria;
- Dokuchaev Soil Institute (DSI), Russia;
- Institute for Rural Economy (IER), Mali;
- Food and Agriculture Organisation of the United Nations (FAO), Italy.

The objectives as defined in the SCATYIELD project were in short:

1. to elaborate a yield condition service demonstrator for the western part of the Sahelian zone of Africa, that is based on ERS-scatterometer based topsoil humidity information;
2. to develop a yield condition demonstrator for Russia, using data (land cover, soil, weather) from the area, adapted soil water balance and crop growth simulation models also based on ERS-scatterometer;
3. to analyse system requirements for operational use in the regions;
4. to facilitate operational and commercial use in a later stage, other international agencies and multinational commercial agri-business organisations would be contacted to discuss operational requirements.

ALTERRA, in close cooperation with IPRS and Dokuchaev Soil Institute, was responsible for the second objective. The research in this objective is based on a merger of a remote sensing application and an agrometerological crop model. Both applications have their roots in the MARS project of the Space Application Institute (SAI) of the Joint research Centre (JRC) at Ispra, Italy. For this SCATYIELD research project the CGMS version 5.2, running on a Sun Unix platform, was used.

As you can read in this report the use of soil moisture based on the ERS-scatterometer in CGMS is promising when compared to the rainfall driven water balance method and when compared to regional statistics. We hope we can continue to further improve this ERS-scatterometer based CGMS in our existing and new study areas.

The authors are grateful to the ESA-DUP programme for allowing us to explore the opportunities of the ERS-Scatterometer, and particular Dr. Pascal Lecomte for his interest and support.

Summary

Soil water is one of the most important parameters influencing crop yield. In hydrological, agronomic and climate (change) studies and monitoring systems, soil water is usually simulated using water budget models. These models require a large amount of expensive input data (rainfall, evapotranspiration) and still may not be very accurate, therefore they are unattractive when you need areal values of soil moisture for large, extended agricultural areas in semi-real time. In such a case areal values of soil moisture should be provided by an accurate and cost-effective remote sensing based method. In this project the soil moisture used is measured directly from ERS-scatterometer by separating information from vegetation reflectance through a particular method of processing based on the respective measurements of the three antennae present on ERS-scatterometers. The particular method of processing permits to separate vegetation effects from topsoil water information.

In this project the aim is to develop, validate and demonstrate a method using data from the ERS-Scatterometer for detecting and monitoring regional droughts over large areas in European Russia and Ukraine, and for quantifying the effects of drought in terms of crop yield reduction. The method is based on the Crop Growth Monitoring System (CGMS), developed in the framework of the MARS project for the European Commission. The standing CGMS method uses a soil water balance, which, in this study we refer to as the balance method. For the current study an alternative for the soil water balance method was designed by replacing the soil water balance calculations in CGMS by a soil moisture estimate from ERS-scatterometer data. We call this new method the scat method.

In this study the overall approach to the validation of the new scat method was to compare its results with those of the standing CGMS method, and with regional yield statistics. As the latter are given at oblast (province) level, yield reductions calculated with the scat method and with the balance method had to be aggregated to oblast level. The aggregated results of both methods were then compared with each other and with the reported yield reductions at oblast level. Finally, the scat method is applied for the current year 1999 to generate drought stress values during the growing season for each decade.

To carry out simulations with the scat method and the balance method first an extensive database has been built. The data in the study area, situated in Russia and Ukraine, covers weather data, soil water index based on the ERS-scatterometer, soil map, crop data, land cover and yield statistics. Next the scat and balance method are applied to simulate drought affected yield for the years 1994 up till 1997.

For two of the four years (1994 and 1997) the scat method gives drought stress values on oblast level that are similar to the regional statistics. For 1995 the scat method gives more drought stress in the north and for 1996 the scat method gives more drought stress in the south. A major part of the differences between both

methods (scat and balance) and the regional statistics can be explained by the quality of input data and limitations in methods which both can be improved.

Important input data to improve are related to crops. Attention should be paid to implement the right local varieties in the database. Sowing dates should be derived from ERS-scatterometer data in combination with other remote sensing sources to indicate soil moisture and temperature status around sowing. To monitor the drought stress in semi-real time with the scat method it would advisable to have real time data about temperature, irradiation, wind speed, vapour pressure of some main synoptic stations. This way the effect of variations in these variables are quantified in the estimates of drought affected crop yield.

Regarding the methodology, both the scat and balance method can be improved. The conversions from m_s to SWI and SWI to an absolute soil moisture in the scat method are not specified for spatial variations in soil physical properties or seasonal variation in evapotranspiration. Also the estimates for initial soil moisture at sowing in areas with frost and snow are unreliable in both methods. The water balance in the balance method should be extended with more layers to make the estimated soil moisture in the upper part of the rooting zone more sensitive for small rainfall events. Of course in the framework of this project the latter improvement is only relevant to validate the scat method with the balance method.

The response to drought stress in CGMS, which is equal in both methods, has a few shortcomings. The drop of soil moisture below the critical soil moisture lead to a sudden decline in growth. In reality damage from drought builds up more gradually: better water consumption strategy or by getting water from the subsoil below the main rooted zone. The description of death of leaves due to drought stress could be improved as well. In CGMS it is assumed that here is accelerated decay leading to immediate death of the eldest leaf age classes, but it does not affect the ageing of younger leaves. Finally, the effect of drought stress on yield depends on crop stage. Many crops are more sensitive to stress during a critical period such as flowering. This is not included in CGMS.

A future project should include the above listed improvements. Next, new simulations for the Russian-Ukrainian study will indicate how drought affected crop yields of the scat method fit with the regional yield statistics and the balance method. For this it is important to collect yield statistics of more oblasts and more years.

1 Introduction

1.1 Background

Soil water is one of the most important parameters influencing crop yield. In hydrological, agronomic and climate (change) studies and monitoring systems, soil water is usually simulated using water budget models that require expensive field measurements and/or expensive rainfall data which are point based. These models are unattractive when you need areal values of soil moisture for large, extended agricultural areas in semi-real time. In extended agricultural areas with a low density of meteorological observations in relation to the spatial variability of rainfall interpolation procedures will give inaccurate estimates of areal values of soil moisture. The accuracy of the estimates also depends on the water budget model used and the quality of additional data needed for such a model. Therefore it is attractive to have a remote sensing based method that directly provide areal measures of soil moisture in stead of using point based rainfall data and water budget models. Of course it is only attractive if those methods are accurate and cost-effective. An additional advantage is that the remote sensed data can be used in semi-real time which is important to monitor drought stress.

There is a remote sensing based method that have the potential to provide soil water information on a very cost-effective basis. The soil moisture is measured directly from ERS-scatterometer data by separating this information from vegetation reflectance through a particular method of processing based on the respective measurements of the three antennae present on European scatterometers. The particular method of processing permits to separate vegetation effects from topsoil water information (Wagner, 1998).

The project described in this report is the follow-up of a former project called ‘Application Service Demonstrator for Drought Early Warning in Mali Based on ERS-Scatterometer Information’. This former project was submitted in the framework of European Space Agency (ESA)‘s Data User Programme (DUP) and started in December 1997 and lasted till February 1999. The follow-up project, also part of the same framework, aimed to introduce new study areas and crop growth models to calculate crop performance indicators. The objectives as defined in the project were in short:

- to elaborate a yield conditions service demonstrator for the western part of the Sahelian zone of Africa, that is based on ERS-scatterometer based topsoil humidity information;
- to develop a yield conditions demonstrator for Russia, using soil data from the area, ERS-scatterometer based topsoil humidity information, adapted soil water balance and crop growth simulation models;
- to analyze system requirements for operational use in the regions;

– to facilitate operational and commercial use in a later stage, other international agencies and multinational commercial agri-business organizations will be contacted to discuss operational requirements.

This report concentrates on second item: ‘develop a yield conditions demonstrator for Russia…’.

1.2 Aim of the study

The aim of the underlying study is to develop, validate and demonstrate a method using data from the ERS-Scatterometer for detecting and monitoring regional droughts over large areas in European Russia and Ukraine, and for quantifying the effects of drought in terms of crop yield reduction. In previous documents the method is called ‘scat-data based service demonstrator for drought warnings’.

Development

In this study the ‘scat-data based service demonstrator for drought warnings’ is based on the Crop Growth Monitoring System (CGMS), developed in the framework of the MARS project for the European Commission. CGMS is extended to use scatterometer data as dynamic input to the crop model besides the weather data (rainfall and evapotranspiration). The standing CGMS method uses a soil water balance, which, in this study we refer to as the (soil water) balance method. For the current study an alternative for the soil water balance method was designed by replacing the soil water balance calculations in CGMS by a soil moisture estimate from scatterometer data. We call this new method the scat method.

Validation

In this study the overall approach to the validation of the new scat method was to compare its results with those of the standing CGMS method, and with regional yield statistics. As the latter are given at oblast (province) level, yield reductions calculated with the scat method and with the balance method had to be aggregated to oblast level. The aggregated results of both methods were then compared with each other and with the reported yield reductions at oblast level. For the crop we have chosen barley.

However, the balance method and the scat method can also be compared very easily at the more detailed level of a single grid cell, the basic climatic area unit used in CGMS. In addition, at grid cell level the changes in soil moisture content during the growing season can be compared. This allows a more exact interpretation of the differences than the comparison with the regional statistics at oblast level, and may lead to detection of anomalies in both methods. In this way, the performance of the scat method is compared with that of the standing CGMS, here referred to as the balance method. In fact, it is as much a validation of balance method as of the scat method.

Demonstrate

The ‘scat-data based service demonstrator for drought warnings’ is applied for the current year 1999 to generate drought stress values during the growing season for each decade. This semi real time monitoring of the yield conditions in Russia and the Ukraine is shown on internet (www.neo.nl/scat).

1.3 Potential and risks of the study

It was anticipated that the study region offered a great potential for such an application as described in section 1.2, because it forms a vast slightly undulating plain where cereal cropping forms the dominant kind of land use, while the climatic conditions range from rather humid in the north to somewhat drought-prone in the south. It has a continental climate with cold winters and regular snow cover, especially in the northern parts. As major possible obstacles to successful application were mentioned the difficulty to estimate the soil moisture conditions in winter and spring under a regime of snow cover and snow melt, and of frozen and thawing soils. A related problem would be the difficulty to estimate a plausible sowing date for the various crops. Apart from the environmental problems it might prove difficult to collect sufficient data on weather, soil moisture, crop and crop calendar to calibrate and validate the proposed calculation procedures.

1.4 Outline of the report

This report describes first how CGMS will be used as a service demonstrator for drought warnings using data from the ERS-scatterometer (chapter 2). Next, the study area is introduced and data needed to test and validate CGMS are discussed (chapter 3). Results of the scat method and balance method in CGMS are compared and analyzed in chapter 4. The last chapters 4 and 5 contain conclusions and recommendations.

2 CGMS as service demonstrator for drought warnings

This chapter describes two different methods to calculate drought stress. Both methods, implemented in CGMS, use WOFOST as model to translate dynamically soil moisture conditions into estimates of yield reduction due to drought stress. One method uses soil moisture contents based on the ERS-scatterometer; the other calculates soil moisture contents by simulating a daily water balance for the rooting zone using rainfall and evapotranspiration according to Penman. In this and following chapters the method based on the ERS-scatterometer is called scat method and the method based on the water balance is called balance method. The methods differ from each other only in the way that the soil moisture is derived.

Because both methods have the same crop growth model, WOFOST, this model is first described (2.1). Then section 2.2 describes the Crop Growth Monitoring System (CGMS). CGMS is a tool that enables regional application of WOFOST. It combines the database (storage of input and output data of WOFOST for different simulation units), WOFOST and data-processing procedures (e.g. interpolation of weather data, spatial aggregation of results). When CGMS is mentioned it also refers to WOFOST. This chapter ends with an explanation and discussion how the soil moisture is derived in both methods (2.3).

2.1 WOFOST

To calculate the yield reduction we use the crop growth model WOFOST (Boogaard et al, 1998; Supit et al., 1994). WOFOST simulates the daily growth of a specific crop, given selected weather and soil data. For each simulation, you select specific boundary conditions, which comprise: the sowing date and the soil's initial water status. WOFOST follows the hierarchical distinction between potential and limited production. Light interception and CO_2 assimilation are the growth driving processes, and crop phenological development the growth controlling processes.

Like all mathematical models of agricultural production, WOFOST is a simplification of reality. In practice, crop yield is a result of the interaction of ecological, technological and socio-economic factors. In WOFOST, only ecological factors are considered under the assumption that optimum management practices are applied.

WOFOST is one-dimensional and mechanistic. Its application to regions relies on the selection of representative points, followed by spatial aggregation or interpolation.

2.2 CGMS

To use WOFOST in a regional application CGMS (Crop Growth Monitoring System) has been developed (Vossen and Rijks, 1995; Van Diepen et al., 1998; 1995). In CGMS, WOFOST is linked to an ORACLE relational database and Arc/Info-GIS.

2.2.1 MARS-CGMS

The original CGMS is operated by the MARS project at JRC, Ispra, Italy, since 1994 and is used for the routinely monitoring of the agricultural season, across Europe, and adjacent regions. The MARS-CGMS covers Europe up to the Ural, Turkey and the Maghreb. The spatial resolution is 50x50 km, the temporal resolution is one day. The CGMS monitoring deals with the quantification of the terms of the climatic water balance, and with the quantification of yield and the yield reduction due to drought stress. For this, the standing CGMS method uses the soil water balance of the WOFOST model, which, in this study we refer to as the (soil water) balance method.

2.2.2 CGMS as scat-data based service demonstrator for drought warnings

The Crop Growth Monitoring System (CGMS), developed in the framework of the MARS project for the European Commission, has a similar purpose as the intended scat-data based service demonstrator for drought warnings in Russia and Ukraine. The major difference between the two approaches is that the scat based drought detection system uses soil moisture based on scatterometer data as dynamic input to the crop model where CGMS uses rainfall and evapotranspiration data. Because of its functional similarity CGMS represents a suitable toolkit and working environment for the realization of this study.

Technically, CGMS has been used in several ways in the current study:

- as GIS based working environment (its user interface, data base model, linkage of models, interpolation module, visualization of maps);
- as data base to store weather data, geographical data, and crop data;
- as framework to develop the new method of drought assessment based on the scatterometer data (the scat method);
- as a tool to calculate yield reductions with the scat method and the standing balance method in CGMS.

It should be understood, that CGMS at the start of this study was an empty system, and had to be filled with data and maps specifically collected for this study (weather, soil map, grid map, administrative map).

2.2.3 Functions in CGMS besides WOFOST

The most important issue for the regional application is the interpolation of the weather data from weather stations to centers of a climatic grid cells. These grid cells are assumed to be homogeneous regarding the weather. Annex 1 describes the interpolation procedure in CGMS. For each center of a grid cell the values of the variables temperature, radiation, air humidity and wind speed are the average of the values of weather stations that are most similar to the grid cell center based on meteorological distance (see Annex 1). In case of rainfall a grid gets the value of the most similar weather station, again based on meteorological distance (see Annex 1).

Data of the soil map is used as input in the calculation of the water balance. Soil moisture contents at different pressure heads (saturation, field capacity, wilting point) determine the water retention of the soil. Besides, the soil map is used to estimate the suitability of soils for different land use forms.

The climatic grid and the soil map are combined in an overlay-procedure. This results in a number of unique simulation units for CGMS (combinations of climatic grid cell, rooting depth and water retention curve). For these simulation units potential and water-limited biomass are simulated with the WOFOST model in CGMS. The total above ground biomass is composed of different plant organs: leaves, stems, grains. CGMS aggregates the daily biomass values per simulation unit into decade values per climatic grid cell. The ratio between water-limited and potential biomass or grains is a indicator for drought stress.

2.3 Modelling of soil moisture in CGMS

The soil moisture module in CGMS is modified to enable water-limited crop growth based on observed scat data transformed into the Soil Water Index (SWI). Both ways of deriving soil moisture are described below.

2.3.1 Soil moisture estimated from ERS-scatterometer data

In the scat method the soil moisture content is derived from Soil Water Index (SWI). This SWI expresses soil moisture for the whole rooting depth on a relative scale from 0 (driest observation) to 100 (wettest observation). First, the Technical University of Vienna has derived SWI from m_s: a relative soil moisture that is valid only for the top soil layer (5 cm).

Conversion m_s into SWI

To convert the m_s into SWI a simple two-layer water balance method is considered described by Wagner (1998). The first layer represents the remotely sensed topsoil layer, and the second layer which extends downwards from the bottom of the surface layer is assumed to be a reservoir that has no contact to the outside world other than via the surface layer. In this model, the water content in the surface layer is highly dynamic due to various processes such as precipitation, evapotranspiration, and surface runoff. The water content in the reservoir varies only slowly because its rate of change is limited by the amount of water that can be exchanged with the surface layer. The water flux between the two layers is assumed to be proportional to the difference of the volumetric moisture content in the surface layer and in the reservoir.

In this model the water content in the reservoir is fully explained by the past dynamics of the surface soil moisture content. More recent events have stronger impact on the reservoir water because of the exponential weighting function.

The conversion of m_s into SWI is shown by the next formula (Wagner, 1998).

$$SWI(t) = \frac{\sum_i m_s(t_i) * e^{-\frac{t-t_i}{T}}}{\sum_i e^{-\frac{t-t_i}{T}}} \qquad for \quad t_i \leq t$$

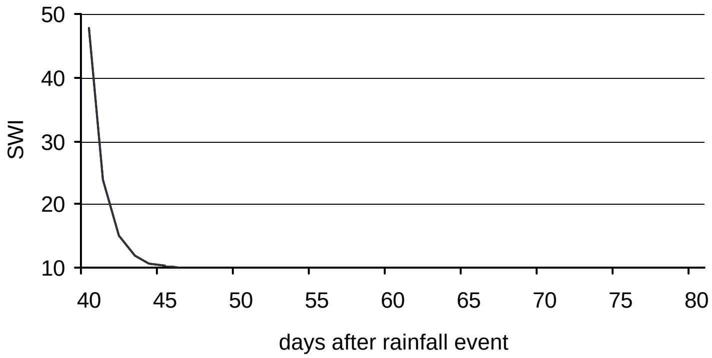
SWI(t) = soil water index of sub surface (second) layer at time t
$m_s(t)$ = relative soil moisture of the surface layer based on scat data at time t_i
T = characteristic time length (20 days).

The variable T increases with depth of rooting and decreases with the pseudo-diffusivity constant C, which depends on soil properties. This formula controls how fast the soil reacts on rainfall events on the soil surface. Variability in rooting depth and conductivity between soils will lead to different time-series of SWI: more gentle or more fluctuations. The variable T is determined by calculating the correlation between SWI and ground observations in the 0-20 cm and 0-100 cm layers from 211 fields for T-values ranging between one and hundred days and by determining T where the highest correlation is observed (Wagner, 1998).

Example of conversion m_s into SWI

To understand the conversion of m_s into SWI we give a small example. Suppose the theoretical case that m_s has value 10 for 40 days and suddenly the m_s changes for one day into value 70 and the next 40 days the m_s value returns to the level of 10. The SWI-value at day 41 not equals the value 70 but is much smaller: only 13.4 (see fig. 1, bottom graph). This is due to all the other 10-values before day 41 which are taking into account (the longer ago, the lower the weight; see formula). Still after 40 days (on day 80) this high 70-value of m_s influences the value of SWI.

The influence of m_s on SWI depends on the characteristic time length: in this case 20 days. A characteristic time length of one day would have lead to a SWI-value of 47.9 on day 41 and a quicker return of the SWI-value back on the level of 10: six days in stead of more than 40 days for the characteristic time length of 20 days (see fig. 1 top graph).



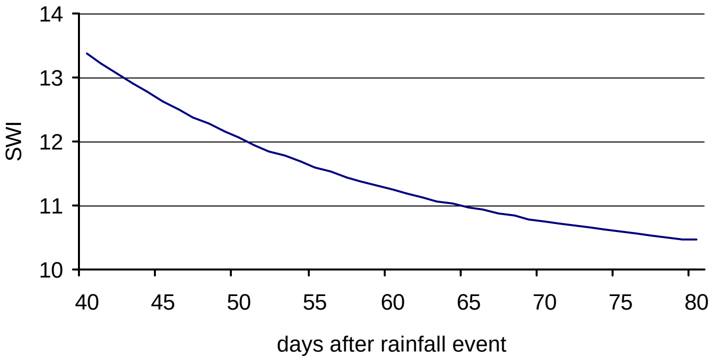


Fig. 1 Example of influence of m_s *value of 70 on the SWI for the next 40 days for a characteristic time length of 1 days (top) and 20 day (bottom).*

Conversion SWI into absolute soil moisture

In the scat method the absolute soil moisture (SM_{scat}) is derived from SWI. It would be attractive when field capacity is used as highest value for SWI and wilting point as lowest value. Then SWI stands for the fraction of soil moisture between field capacity and wilting point. Also the fraction not easily available water for a plant in WOFOST is expressed between field capacity and wilting point resulting in the critical soil moisture. This means that you only have to compare SWI with the fraction not easily available water to know whether drought stress will occur. And then variability in soil water retention curves does not give different values for drought stress for a certain value of SWI because both, SWI and fraction not easily available water, are expressed on the same scale. So it depends on the choice of conversion of SWI into SM_{scat} whether variability of soil water retention curves influences the conversion of SWI into absolute soil moisture.

However, in this study the conversion of SWI into SM_{scat} field capacity is not related to the highest value of SWI. The highest value of SWI is half way field capacity and saturation. This is based on Ukrainian data with mostly well drained loamy soils. See also the next formula defined by Wagner (1998).

$$SM_{scat} = SM_{wp} + \left(\left(\frac{SM_{sat} + SM_{fc}}{2} \right) - SM_{wp} \right) * \frac{SWI}{100}$$

SM_{scat} = volumetric soil moisture derived from SWI ($cm^3.cm^{-3}$)
SM_{wp} = volumetric soil moisture at wilting point ($cm^3.cm^{-3}$)
SM_{fc} = volumetric soil moisture at field capacity ($cm^3.cm^{-3}$)
SM_{sat} = volumetric soil moisture at saturation ($cm^3.cm^{-3}$)
SWI = Soil Water Index, relative soil moisture derived from ERS-scatterometer

For other type of soils this rule could be different. For coarse sandy soils the highest SWI value could be more towards field capacity than towards saturation and vice versa for a clay soil under wet conditions (bottom of a valley). However, there was not enough data to support modification of soils other than loamy soils (Wagner, pers. comm.). Furthermore attention should be paid to the influence of ground water. When ground water has significant influence on the soil moisture in the rooting zone, the SWI is less suitable as an indicator for the average soil moisture in the rooting zone.

Because of the above formula differences in water retention curves between soils have influence in the way SWI is converted into a soil moisture content. See for example the next table that shows the conversion of SWI into a soil moisture content for two different soils. Both soils have the same available water capacity of 0.20 (difference in soil moisture content between field capacity and wilting point) but different moisture contents between saturation and field capacity (0.20 for A and 0.05 for B).

Table 1 Example how SWI is converted into a soil moisture content for two different soils (volumetric moisture content at saturation ($?_{sat}$), at field capacity ($?_{fc}$), at wilting point ($?_{wp}$))

	$?_{sat}$	$?_{fc}$	$?_{wp}$	SWI	SM_{scat}
Soil physical group A	0.45	0.25	0.05	30.0	0.14
Soil physical group B	0.35	0.30	0.10	30.0	0.17

The two different soils have different soil moistures (SM_{scat}) for the same SWI value. Suppose the fraction not easily available water (depending on crop physiology and weather data) of the soil moisture between field capacity and wilting point is 0.4 then the critical soil moisture contents are 0.13 and 0.18 respectively for soil physical group A and B. In this situation soil physical group B will have drought stress (SM_{scat} of 0.17 is lower than 0.18) while soil physical group A is still not affected by drought (SM_{scat} of 0.14 is higher than 0.13).

2.3.2 Soil moisture estimated from water balance

The soil moisture content in the root zone follows from the daily calculation of the water balance driven by weather data. In CGMS three different soil water sub models are distinguished. The first and most simple soil water balance applies to the potential production situation. Assuming a continuously moist soil, the crop water requirements are quantified as the sum of crop transpiration and evaporation from the shaded soil under the canopy.

The second water balance in the water limited production situation applies to a freely draining soil, where groundwater is so deep that it can not have influence on the soil moisture content in the rooting zone. The soil profile is divided in two compartments, the rooted zone (RD_{act})and the lower zone between actual rooting depth and maximum rooting depth (RD_m). The subsoil below the maximum rooting depth is not defined. The second zone merges gradually with the first zone as the roots grow deeper.

The principle of this soil water balance is a cascade (overflowing bucket) (see fig. 2). The rainfall (R) infiltrates, a part may be temporarily stored above the surface (SS) or runs off (SR). Evapotranspiration loss (E and T) is calculated. The infiltrated water that exceeds the retention capacity of a soil compartment percolates downward (PC). There is no capillary rise (CR). Water supply by irrigation or surface run-off from higher positions on the slope is not taken into account in CGMS. However, it is possible to specify a water supply schedule from irrigation by adding the water supply by irrigation to the daily rainfall

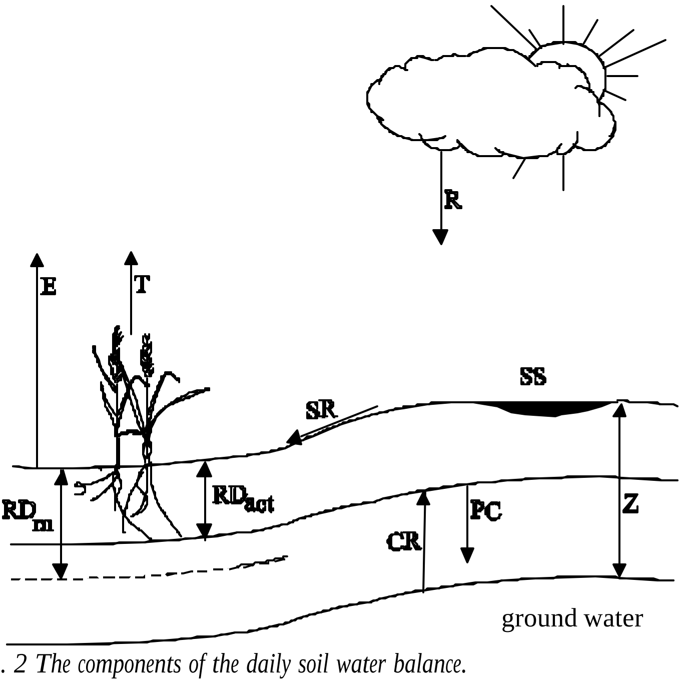


Fig. 2 The components of the daily soil water balance.

2.3.3 Effect of soil moisture on crop growth

The soil moisture is important to determine whether the crop has water stress. To avoid desiccation, a crop must compensate for transpiration losses, by water uptake from the soil. In the WOFOST model in CGMS, an optimum soil moisture range for plant growth is determined as function of the evaporative demand of the atmosphere (reference potential transpiration of a fixed canopy), the crop group and total soil water retention capacity. Within that range, the transpiration losses are fully compensated. Outside the optimum range, the soil can either be too dry or too wet. Both conditions lead to reduced water uptake by the roots, in a dry soil due to water shortage, in a wet soil due to oxygen shortage.

A crop reacts to water stress with closure of the stomata. As a consequence, the exchange of CO_2 and O_2 between the crop and the atmosphere diminishes, and hence CO_2-assimilation is reduced. This effect is quantified assuming a constant ratio of transpiration to gross assimilation. This is done according to next formula, where the assimilation rate A is the product of the potential assimilation rate A_p (both [kg•ha^{-1}•d^{-1}]) and the ratio of the actual (water-limited) transpiration rate T_a and the potential transpiration rate T_p (both mm•d^{-1}) (Van Keulen and Wolf, 1986).

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

The potential transpiration rate depends on the leaf area and the evaporative demand of the atmosphere. The evaporative demand is characterised by radiation level, vapour pressure deficit and wind speed. In CGMS, potential transpiration is calculated according to the Penman formula (Penman, 1956), adapted according to Frère and Popov (1979). The potential transpiration is calculated for a reference crop. Differences between crops can be accounted for with a correction factor, having a value of 1.0 for most crops. A plausible range for this factor is 0.8 for water saving crops and 1.2 for crops spending relatively much water.

The relation between soil water content and the ratio T_a/T_p is shown in fig. 3. Between the critical soil moisture content (θ_{cr}) and field capacity (θ_{fc}), the ratio is 1, allowing potential transpiration. Outside this range, the ratio is smaller than 1, leading to reduced transpiration. At the permanent wilting point, θ_{wp}, and at the saturation point θ_{st}, transpiration and hence crop growth, come to a halt. θ_{wp}, θ_{fc} and θ_{st} depend on soil type. θ_{cr} depends on crop physiology and weather. A combination of high evaporative demand and drought-sensitive crops lead to high values of θ_{cr}. A crop's drought-tolerance is indicated with a soil depletion number, within the range of 1.0 for drought-sensitive crops and 5.0 for drought tolerant crops (Driessen 1986a; Doorenbos and Kassam, 1979).

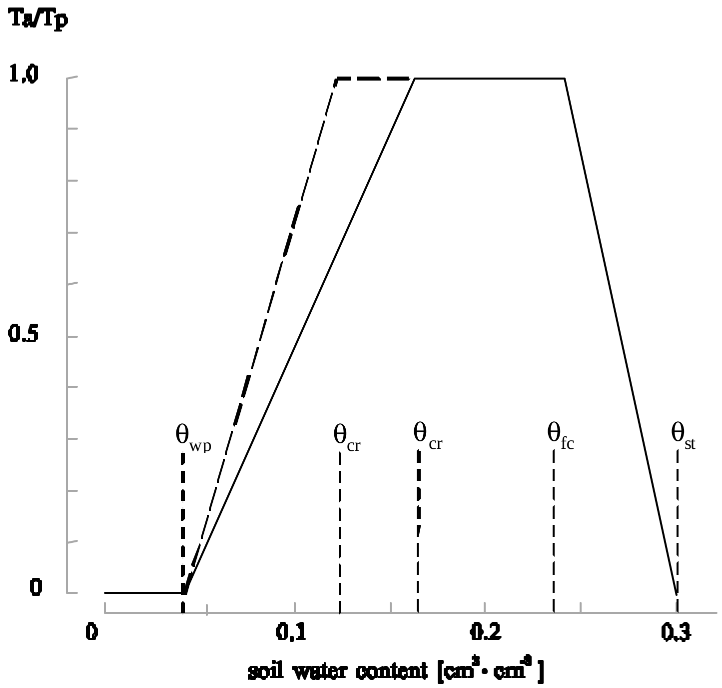


Fig. 3 The relation between soil water content, q*, and* T_a/T_p *for a crop/soil combination.* q_{wp}*,* q_{cr}*,* q_{fc} *and* q_{st} *represent the water content of the soil at wilting point, the critical point for potential transpiration, field capacity and saturation, respectively. The dashed line represents either a more drought resistant species under the same field conditions, or the same species under a lower evaporative demand, caused by different weather conditions (Penning de Vries et al., 1989; Van Laar et al., 1992)*

The response to drought stress in CGMS is rough (Van Diepen et al., 1998). The currently applied simple soil water sub model may lead to a sudden decline in growth in response to increasingly severe drought conditions. In reality the damage from drought builds up more gradually, either by a better water consumption strategy than suggested in the model, or by getting water from the subsoil below the main rooted zone.

The description of death of leaves due to drought stress could be improved as well. In CGMS it is assumed that here is accelerated decay leading to immediate death of the eldest leaf age classes, but it does not affect the ageing of younger leaves. According to the model the premature death of part of the leaves sometimes has a beneficial effect by lowering the respiration requirements while not affecting the assimilation rate which is the case as long as there are enough leaves left. Some time after the drought period the model indicates no after-effect. A solution is to increase the physiological age of all leaves in response to drought stress. The exact mechanism and parameterization of this has yet to be described.

In the model the effects of drought stress are quantified as reduction of assimilation, which leads to reduction in biomass formation. In reality, the effect of such a reduction on yield depends on crop stage. Many crops are more sensitive to stress during a critical period such as flowering. If flowering fails, there will be no fruits or seeds. This leads to a special case of sink limitation, which is not included in CGMS (Diepen et al., 1998).

Except in the juvenile stage of leaf formation, the growth in WOFOST in source limited. In reality, the capacity of organs to grow in size and weight is often limited. For cereals the number of grains sets a ceiling to maximum yield because of the maximum size of a grain or because of the maximum capacity of the internal transport of assimilates to the grains. In such a case the growth is called sink limited, as opposed to source limited. In the model the sink limitations are not accounted for (Diepen et al., 1998).

3 Data

To carry out simulations with the scat method and the balance method first an extensive database is built. The data in the study area (3.1) covers weather data (3.2), soil water index based on the ERS-scatterometer and measured soil moisture (3.3), soil map (3.4), crop data (3.5), land cover (3.6) and statistics (3.7).

3.1 Study area

The study area is situated in Russia and Ukraine. Longitude is between 30 and 42 degrees East; the latitude is between 44 and 56 degrees North (see fig. 4). The land area is approximately 1.1 million square kilometres.

The technical university of Vienna (TUV) defined a grid for the study area for which TUV provides data about soil moisture indicators. Each grid cell has a size of 0.25 x 0.25 degree (so a batch of 1° x 1° is divided into 16 grid cells). Therefore the size of the grid cell is not constant (on average 25 by 25 km). This grid is used in CGMS as the climatic grid. The weather data of stations is interpolated to each centre of a grid cell (see 3.2).

Fig. 4 Study area in Russia and Ukraine, with oblasts and cities

3.2 Weather data

3.2.1 Variables needed for CGMS

Weather data is needed to simulate the daily biomass production, the daily crop development and the daily water balance. Simulation of the water balance is only relevant for the balance method. Variables needed in the simulations are daily values of:

- minimum temperature (°C);
- maximum temperature (°C);
- irradiation ($kJ.m^{-2}.d^{-1}$);
- vapour pressure (mbar);
- wind speed ($m.s^{-1}$);
- rainfall ($mm.d^{-1}$).

3.2.2 Variables available

For this study daily weather data of NOAA is used for the years 1994 - 1998 for 120 weather stations. For rainfall many hourly observations are missing leading to an underestimate of total daily rainfall. Therefore rainfall is taken from an other data source (meteoconsult) which comprises 71 weather stations. Most of these weather stations have missing records (days) or missing values of one of the variables on a certain day. This is solved by completing the data set indicating these records have unknown data (-99). In the weather interpolation procedure of CGMS unknown values are replaced with long term average values, except for rainfall. When a station has a missing value for rainfall this station is skipped for the specific day and rainfall of an other station is used.

The NOAA-data contains:

- minimum temperature (°C);
- maximum temperature (°C);
- dew point (°C);
- wind speed ($m.s^{-1}$).

The meteoconsult data contains:

- rainfall ($mm.d^{-1}$).

3.2.3 Calculation of irradiation and vapour pressure

From the above appears that the variables in the NOAA data set do not completely satisfy the data needs of CGMS. Irradiation and vapour pressure have to be derived from other variables. First, irradiation is derived from temperature data with the Hargreaves formula (Van Kappel and Supit, 1998):

$$S_{g,d} = C_a * \frac{S_o * 86400}{1000} * \sqrt{T_{max} - T_{min}} - C_b$$

$S_{g,d}$ = incoming daily global radiation ($kJ.m^{-2}.d^{-1}$)
S_o = daily extra-terrestrial radiation ($J.m^{-2}.s^{-1}$)
T_{max} = maximum daily air temperature (°C)
T_{min} = minimum daily air temperature (°C)
C_a = empirical constant, 0.15 (-), varies over days in year and latitude
C_b = empirical constant, 0.0 ($kJ.m^{-2}.d^{-1}$), varies over days in year and latitude

The incoming daily global radiation (S_o) is calculated with the Angot subroutine in WOFOST and described in the system description of WOFOST 6.0 (Supit et. al, 1994). The empirical constants are estimated for underlying study by visual interpretation of maps showing spatial variation of Hargreaves constants (Van Kappel and Supit, 1998).

Secondly, vapour pressure is derived from available variables with a formula defined by Goudriaan (1977):

$$e_s = 6.10588 * e^{\frac{17.32491 * t_d}{t_a + 238.102}}$$

e_s = vapour pressure at saturation at dew point temperature (mbar)
t_d = air temperature at dew point (°C)
t_a = mean daily temperature (°C)

We know the air temperature at dew point (t_d) and the mean daily temperature (t_a) which together leads to vapour pressure at saturation at dew point temperature. The latter is equivalent to density of vapour at the reference temperature. Now we have vapour pressure for the mean daily temperature.

3.2.4 Interpolation from stations to grid cells

Daily values of all variables (minimum temperature, maximum temperature, irradiation, vapour pressure, wind speed and precipitation) are interpolated from the weather stations to the centre of the 1965 grid cells for the years 1994 up till 1998. For each grid cell the values of temperature, irradiation, vapour pressure and wind speed are the average of the values of weather stations that are most similar to the grid cells based on meteorological distance (see Annex 1). The number of stations used to calculate the average for a grid cell varies between 1 to 4 stations.

In case of rainfall a grid cell gets the value of one station: the most similar weather station, again based on meteorological distance (see Annex 1). When a rainfall observation is missing a value is taken from a rainfall station that is second best in terms of meteorological distance, and so on up till seven stations.

When running CGMS using the scat method rainfall is skipped. All other weather variables are needed for both methods (scat method and balance method) to simulate the development of the crop (temperature), assimilation rates (temperature and irradiation), evaporative demand (irradiation, temperature, vapour pressure and wind speed).

To monitor 1999 we can not use real time weather data because in this study this data is not available on time. As alternative CGMS is run with long term average data for the variables minimum and maximum temperature, irradiation, vapour pressure and wind speed. Rainfall is not relevant because in 1999 we only apply the scat method. The long term average is the daily average of the years 1994 to 1998. In case of missing values this daily average can also be based on less than these five years. One year is the absolute minimum. All stations that have less than 366 values for the long term average (because one day misses in all years) are excluded for the interpolation to the grid.

Most interesting variable to study is the interpolated rainfall. Although not all 71 rainfall stations have observations for each year and short distance variations of rainfall occur, there are still enough stations per year with a good spread through the study area to produce useful rainfall maps as input for the balance method and for analysis of the results. Annex 2 presents maps of monthly rainfall in the growing season (April - July) for 1994 – 1997.

3.3 Soil moisture

3.3.1 ERS-scatterometer

The soil water index (SWI) and surface soil moisture (m_s) are provided by TUV for each grid cell centre and on a daily basis for 1994 - 1999. Actually there is no daily observation by the ERS-scatterometer. The frequency is one value per 2 or 3 days. A day without an observed value is filled with the previous (earlier) observation.

3.3.2 Observations

Besides soil moisture estimated with ERS-scatterometer, there are also in the field observed soil moisture values. The soil moisture is measured at agro-meteorological stations in Russia and Ukraine for different crops (barley, winter wheat, spring wheat, maize), for different time steps in spring and summer (3 times a month on the 8th, 18th, 28th of each month), and for different soil depths (0-5 cm, 0-10 cm, 0-20 cm, 0-50 cm, 0-100 cm). Except frequent observations of the soil moisture also main characteristics like soil type, field capacity, volumetric density, and wilting level are known for each observation site.

These detailed soil observations are available for 1992-1996. The data on 1994 - 1996 can be used to compare with soil moisture calculated with the scat method and the balance method.

3.4 Soil map 1 to 4 million

The distribution of soils in Russia and the Ukraine follows a north south zonal pattern, related to climate and geology. The northern half of the study area is covered by glacial sediments, the southern half by aeolian sediments (fine sand and loess). The broad north south climatic sequence of soils in the study area is eutric Podzoluvisols (De), Luvisols (L), Phaeozems (H), Luvic(Cl) and Haplic Chernozems (Ch), Kastanozems (K). The chernozem zone (black earth) has the highest soil organic matter content.

3.4.1 Variables needed for CGMS

The soil map supplies rooting depths and water retention curves both needed to calculate the water retention capacity of a soil in case of the balance method. For the scat method water retention curves are used to convert SWI into an absolute soil moisture content.

Rooting depth is also used to exclude soil units with very shallow rooting depths from the simulations. This soil characteristic is input of the balance method and has a very straight effect on the water limited growth of crops. Very shallow rooting depths have to be excluded because they could influence results on grid cell or even oblast level while in reality farmers will not grow crops on these soils.

Other soil factors like slope, drainage, salinity, alkalinity and other agricultural limitations are not considered in this study to exclude soil units. Because we have data about land use we already know which locations are more or less suitable otherwise they would not grow crops on those locations. Later in the aggregation from climatic grid cell to oblast the land cover data is used to exclude grid cells without barley.

For simulations with CGMS we need for each soil unit:

- soil name according to FAO legend of 1974;
- rooting depth;
- soil physical group with water retention curve.

3.4.2 Variables available

Dokuchaev has compiled a 1 to 4 million soil map. Known soil attributes are:

- code of soil mapping unit;
- soil name (dominant and sub dominant soils) according to FAO legend of 1990;

- moisture content at wilting point for the dominant soil (layer 0-20 cm);
- moisture content at field capacity for the dominant soil (layer 0-20 cm);
- moisture content at saturation for the dominant soil (layer 0-20 cm);
- moisture content at wilting point for the dominant soil (layer 20-50 cm);
- moisture content at field capacity for the dominant soil (layer 20-50 cm);
- moisture content at saturation for the dominant soil (layer 20-50 cm);
- percent of soils with potential rooting depth less than 100 cm (consolidated rocks as a restriction);
- percent of soils with potential rooting depth near 150 cm (consolidated rocks);
- percent of soils with potential rooting depth near 50 cm (ground water table as a restriction);
- percent of soils with potential rooting depth near 100 cm (ground water table as a restriction);
- percent of soils with potential rooting depth near 150 cm (ground water table as a restriction);
- percent of soils with potential rooting depth near 200 cm (ground water table as a restriction);
- percent of soils with potential rooting depth near 300 cm (ground water table as a restriction).

3.4.3 Conversion of soil data

For determining the rooting depth first all soil units have assigned a rooting depth of 140 cm. Next, data about consolidated rocks and ground water tables indicating limitations for rooting depth, provided by Dokuchaev, are used to correct the rooting depth. Finally, a CGMS procedure which determines rooting depth on the basis of the soil name (FAO, 1974) is applied. For the last step the FAO legend of 1990 (FAO, 1990) is converted to the legend of 1974.

For CGMS it is necessary to define a limited number of soil physical groups that are characterised by soil moisture contents at wilting point, field capacity and saturation. For the study area 13 soil physical groups are defined (see table 2). This has been done as follows:

- all unknown values (10% of total area) of volumetric soil moisture contents for wilting point, field capacity and saturation are replaced with average values for the whole study area. For soil layer 0-20 these are respectively 0.09, 0.25 and 0.41 and for soil layer 20-50 these are respectively 0.09, 0.23 and 0.37.
- next, the average available water capacity (awc = moisture content at field capacity minus moisture content at wilting point) is calculated for each soil unit. First the awc is calculated for each soil layer and then the average is determined weighing the thickness of the soil layers (0-20 and 20-50).
- also the average soil moisture between saturation and field capacity is calculated for each soil unit (dw = drainage water). This variable is first calculated for each

soil layer and then averaged for the soil unit taking the thickness of the soil layers into account.

– soil units are classified on the basis of values for awc and dw using intervals of 0.05. This resulted into 13 realistic classes. There were a few classes with very limited number of soil units. These were added to other neighbouring classes. Finally for each class average values of soil moisture contents for wilting point, field capacity and saturation were derived.

The definition of the soil physical groups is focused on the awc and dw because both parameters are important in the scat method and the balance method (see 2.3).

Table 2 Soil physical groups based on the 1 to 4 million soil map (volumetric moisture content at saturation ($?_{sat}$), at field capacity ($?_{fc}$), at wilting point ($?_{wp}$), available water capacity per unit length rooting depth (awc), and drainage water per unit length rooting depth (dw))

Soil physical group	Soil description (FAO, 1990)	$?_{wp}$	$?_{fc}$	$?_{sat}$	awc	dw
1	De	0.03	0.10	0.27	0.07	0.17
2	E	0.04	0.11	0.38	0.07	0.27
3	C, H, K	0.12	0.24	0.31	0.12	0.07
4	De	0.05	0.17	0.29	0.12	0.12
5	Ck	0.13	0.25	0.42	0.12	0.17
6	Ch	0.13	0.25	0.47	0.12	0.22
7	De	0.05	0.19	0.26	0.14	0.07
8	J, De, Gm, H	0.11	0.28	0.40	0.17	0.12
9	O, De, M, C	0.09	0.24	0.39	0.15	0.15
10	M, Ch, Hl	0.09	0.26	0.46	0.17	0.20
11	Cl, Ch	0.13	0.28	0.55	0.15	0.27
12	Hl, Ck	0.11	0.32	0.42	0.21	0.10
13	Ch, Sg	0.14	0.35	0.50	0.21	0.15

In terms of water holding capacity there is no clear spatial pattern, as all soil units may include a range in texture and rooting depth. The soils with the lowest awc are soil physical group 1 and 2. Group 1 includes mainly shallow sandy soils, group 2 shallow soils weathered in soft limestone. The groups with medium values for awc are 3-6, with a mixture of ‘C’ and ‘De’ soils. Soil physical groups 7-11 have still higher awc values, group 8 includes a lot of alluvial soils. Groups 12 and 13 have the highest awc values, these soils are deep medium textured soils high in organic matter content.

Important soil parameters used in the balance method are the awc and rooting depth. Multiplication of both variables gives the total available water in soil profile which the crop can partly (only easy available water) use during the growing season as supplement for rainfall. Besides, both factors determine the capacity to buffer a rainfall event. Areas with high values for awc will not be as sensitive for drought as area with low values. Annex 3 presents the total available water in soil profile for the study area based on the soil map 1 to 4 million.

3.5 Crop data

The crop data needed in CGMS can be divided in data about the crop calendar (sowing, emergence, maturity and data where which variety of barley is grown) and data about crop parameters. The crop parameters refer to, amongst other things, phenology, assimilation and respiration parameters, and partitioning of assimilates to plant organs. We selected barley for our simulations.

3.5.1 Crop calendar

The crop calendar for barley in 1994-1999 is based on data provided by Dokuchaev. It is yearly data about sowing, emergence, flowering and ripening of barley for 25 different vegetation stations. These stations are mainly located in the eastern part of the study area and only cover the years 1995, 1997 and 1998. Dokuchaev also provided long term average values for sowing, emergence, flowering and ripening of barley for 132 other vegetation stations. These stations are mainly located in the middle and the western part of the study area. For simulations in both methods we need sowing or emergence date. We have chosen for sowing date and interpolated (Thiessen polygons) the sowing dates to each climatic grid cell for the available years and the long term average. For the years 1994, 1996 and 1999 the long term average sowing date is used in the simulations.

Annex 4 shows the average and yearly sowing date for barley in the study area, interpolated to each grid cell. The irregular spread of vegetation stations over the study area gives probably bad estimates for Ukraine in 1995, 1997 and 1998 and also a not very reliable estimate for the long term average sowing date in north east of the study area. We considered to apply the long term average sowing date for all years because this long term sowing date looks more logical. On the other hand sowing dates varies much from year to year and missing this variation can have large impact on calculated drought stress. An earlier or later growing season could for example mean that the crop misses or profits a late rainfall event at the end of the growing season.

Despite unreliable estimates of sowing date in the Ukraine, we decided to use the yearly interpolated sowing dates of 1995, 1997 and 1998. In future the sowing date for 1994-1999 should be improved. We could use sowing dates that are derived from the ERS-scatterometer.

3.5.2 Crop parameters

In the European CGMS database only one barley variety is applied. This variety and its crop parameters are adopted to the Russian/Ukrainian database in CGMS. Annex 5 provides a listing of the values for these parameters. In this study area no effort has been made to use regional specific varieties of barley.

3.6 Land cover

Land cover data is used in the aggregation of results of the scat method and the balance method to oblast level. In the aggregation land cover data determines whether a grid cell is included or excluded in the aggregation procedure. The land cover data is expressed in different classes like: forests, water bodies, bogs, arable land etc. Dokuchaev calculated percentages land cover per grid. In case of arable land Dokuchaev also provided crop rotation schemes for each grid cell.

The following rule separates grid cells for the aggregation of barley results: grid cells that have 50% or more arable land on which among others other crops barley is grown are included. For example grid (number 22) has 60% arable land with the following crops: winter wheat, spring wheat, barley and fodder crops. This grid cell will be included in the aggregation. We did not set a threshold for the percentage area of barley. Grid cells where, according the above rule, barley is grown are shown in Annex 6.

3.7 Statistics

To validate the results of the scat method and the balance method we used regional statistics on oblast level. Each year oblast official statistical committees collect yield data from agricultural enterprises in Russia. At collective farms, agronomists as a rule use a method of expert estimation of yield, based on data about crop areas and amount of harvested yield. They estimate yield reduction due to drought stress in relation to the potential attainable yield.

The regional statistics concern 1994-1997 and only the Russian part of the study area. Yield statistics of 1998 and for the Ukraine exist but were at the end of this project still not available.

To make a good comparison only oblasts are included that have more than 50% of their area within the study area. Another condition implies that the oblast must contain a considerable number of grid cells with barley as crop (more than 10%).

4 Drought stress

The scat method is compared with the balance method and regional statistics to understand the possibilities and artefacts of using ERS-scatterometer data in CGMS to estimate drought stress. Section 4.1 and 4.2 explain how this comparison is carried out. Next, in 4.3 up till 4.6 the methods are compared by studying drought stress results of 1994 – 1997. Results of 1998 are not presented because the regional statistics were missing. Finally, the drought stress for 1999 (the current year) is demonstrated with the scat method in CGMS (4.7).

4.1 Comparing methods

Results of the scat-method and the balance-method are compared with regional statistics on oblast (province) level provided by Dokuchaev Soil Institute. Although statistics in general are noted for uncertainties these regional statistics are the best validation data set we could get. The results of both methods should correspond with the regional statistics. Possible causes for differences between the two methods and the regional statistics are:

- uncertainties and/or errors in input data used in the scat method and the balance method of CGMS (data as mentioned in Chapter 3);
- uncertainties and/or artefacts in the scat method and the balance method of CGMS (see model description in Chapter 2);
- uncertainties and/or errors in the regional statistics.

Also the results of the scat-method and the balance-method are compared in relation to each other. Differences in results between the two methods are due to the different ways in which soil moisture contents are calculated and different input data regarding soil moisture (rainfall versus scatterometer data).

The comparison between both methods with the regional statistics and between the methods in relation to each other is expected to give a good insight in the problems and possibilities of both methods to predict drought stress.

4.2 Way of analyzing results

4.2.1 Drought stress

WOFOST, run in the CGMS environment, produces several crop indicators at the end of each decade. CGMS has aggregated the indicators spatially from unique values for all combinations of climatic grid cells, rooting depth and soil physical group to one value per climatic grid. The available crop indicators selected, are:

- grain yield: dry weight of storage organs;
- above ground biomass: total dry weight of above ground plant organs.

The indicators are given for potential crop growth (no water limitation) and for water limited crop growth. The drought stress is derived from the crop indicators with the next formula:

$$\text{Drought stress} = \frac{(\text{crop indicator}_{pot} - \text{crop indicator}_{wl})}{\text{crop indicator}_{pot}} * 100$$

pot = potential crop growth
wl = water limited crop growth

4.2.2 Grid level

On grid level the crop indicators are calculated for all 1965 grid cells. Of course not for all these grid cells barley is grown. So, when presenting crop indicators for barley we make a theoretical assumption that all grid cells have barley. This way we get a map with the potential drought stress for barley in case the whole study area was covered with barley. Presenting crop indicators on grid level gives good insight in the patterns of drought stress through the study area. Besides this visual comparison, the actual data of both methods: scat-method and the balance-method are compared to evaluate the resemblance between the methods. For particular situations results will be analysed within a grid cell to gain better understanding between differences of both methods.

4.2.3 Oblast level

Next, calculated grain yields on grid level are aggregated to oblast level to enable comparison with regional statistics which are given on oblast level. Grain yields are chosen because the regional statistics concern grain yields. For this aggregation spatial data about land cover is used (see 3.6).

4.3 Drought stress 1994

4.3.1 Oblast level

According to the regional statistics there is no drought stress in 1994 in the Russian part of the study area (see Annex 7, fig. C). The scat method gives similar results (see Annex 7, fig. A). Except for the Rostov region with moderate drought stress, all regions have no significant drought stress. Fig. 5 shows the relation between the scat method and the regional statistics.

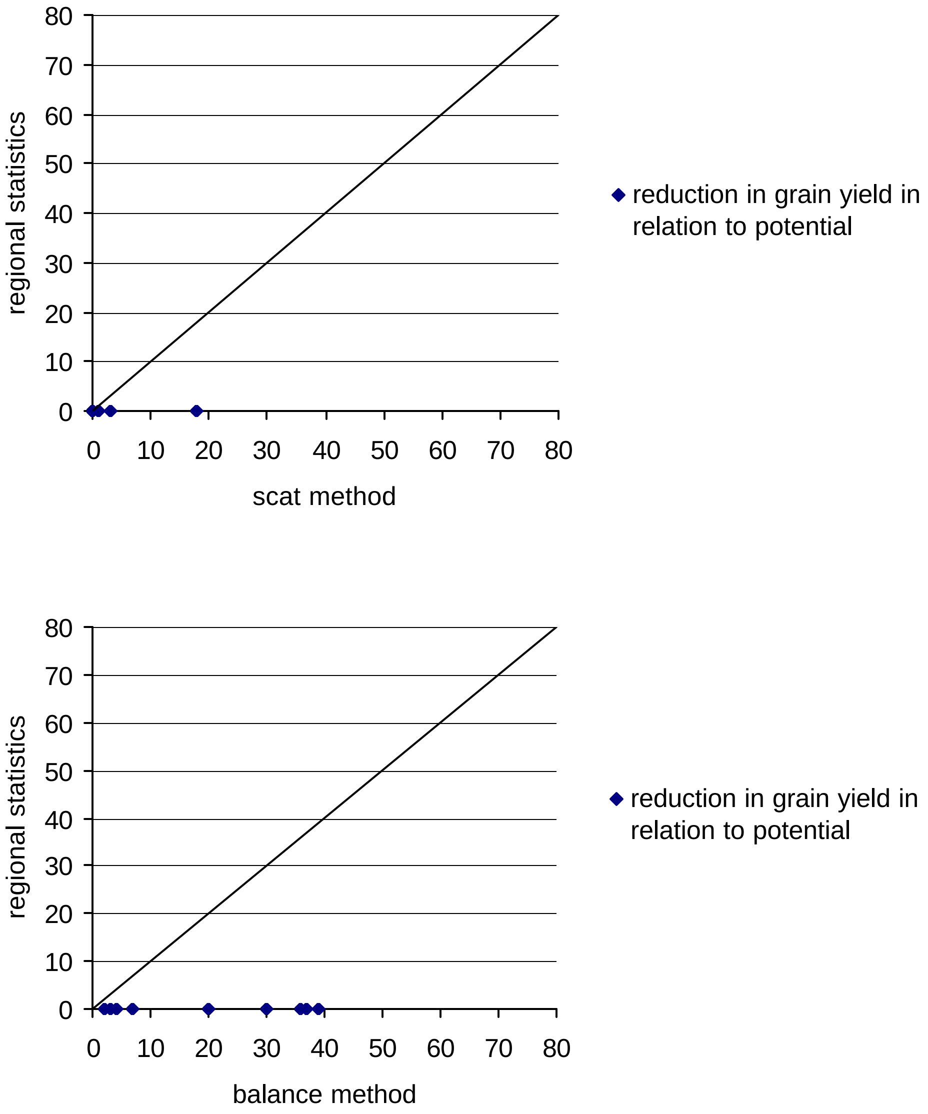


Fig. 5 Comparison of drought stress (water-limited reduction of grains in relation to potential) between scat method and regional statistics (top) and balance method and regional statistics (below) for 1994 in Russia.

Except for the Rostov region all points are located nearby the x-y origin. The moderate drought stress (18%) in Rostov region is due to a group of grid cells with severe drought stress (> 50%) in the western part of the Rostov region (see Annex 8, fig. A).

The balance method results are clearly different compared to the regional statistics and thus also to the scat method (see fig. 5 and Annex 7, fig. B). All southern located regions show mainly high and severe drought stress. The Orel, Kursk, Belgorod and Voronez regions have important drought stress according to the balance method while the scat method and the regional statistics show no or only light drought stress.

Why drought stress in the south simulated with the balance method?

Why do these differences occur in the balance method for 1994? Therefore we look at monthly rainfall data (Annex 2). The south of Russia in the study area shows relatively low monthly rainfall sums: June mainly between 25 and 50 mm and July mainly between 0 and 25 mm. The low rainfall in July in combination with high demand (relatively high transpiration rates in the south) probably caused drought stress in grain yields in the balance method. This also corresponds with the drought stress values based on above ground biomass. These values in the balance method are much lower: almost half of the values of drought stress based on grain yields. Because the bulk of biomass is produced in the vegetative phase which occurs earlier and before the grain filling phase the drought did not affect the biomass as strongly as the grain yields. The production of biomass benefited more from the rainfall earlier in the growing season. For the production of grains this rain was already gone because of evapotranspiration and / or percolation to deep soil layers.

Why no drought stress in the south according to the statistics?

Next question is why the regional statistics does not show the drought stress caused by low rainfall in June and July. There are several explanations. One reasonable explanation is about the crop parameters used for barley in the simulations. These parameters are not tuned for the Russian situation, they follow from the European database in CGMS. Data about the average day of ripening of barley provided by an extended network of vegetation stations in the study area explains that ripening of barley in CGMS is on average two weeks later (second half of July – first week of August) than in reality (first half of July). So, probably in reality the drought in July did not affect crop production as much as in the simulations because the ripening phase of the barley was finished earlier (first half of July).

A similar explanation comes from calibrated crop parameters provided by Dokuchaev, but unfortunately not used in the simulations. These calibrations show that the grain filling stage of barley needs a lower temperature sum compared to barley used in CGMS in Europe. A lower temperature sum (210 ºC lower) means that the grain filling stage lasts shorter; in this case approximately 11 days shorter. Thus CGMS simulates a too long growing season for barley.

Another possible explanation could be that the southern located rainfall stations did not register all rainfall events in July. Precipitation in summer in the study area take place as a rule in form of heavy rains. It means that in many cases the rainfall stations have not registered any rain, but the rain could have taken place at a distance near 1 km from it. However when you study the rainfall pattern in the south (Annex 2), which is based on more than ten stations, the whole south is dry in July. The occasion that all these stations missed rainfall in July is not very plausible. Thus the other explanation about crop parameters seems more reasonable.

Why no drought stress in the south according to the scat method?

Still there is the question why only the balance method shows this drought stress and not the scat method? The crop parameters are equal for both methods so the explanation above is not valid. The differences must be due to the soil moisture module in CGMS and the input data for this module because these are the only differences between both methods.

The different results (scat method shows no drought stress and balance method shows large to severe drought stress) can be explained as follows. The scat method has a more direct and sensitive relation between rainfall and soil moisture than the balance method (see also fig. 7). The few small rainfall events that happen in July cause incidentally peaks of soil moisture. During these peaks there is no drought stress.

For the balance method this is different. When at a certain stage the soil moisture goes considerably beneath the critical soil moisture it needs large rainfall events to set the soil moisture back above the critical soil moisture (see for example fig. 12 at the end of the growing season). Rainfall events larger than the ones in July 1994. This is because the water infiltrated in the soil profile is spread over the whole actual rooting zone. Especially for deep rooting depths it takes a lot of water to increase the soil moisture. For example: to increase the soil moisture in a soil having a rooting depth of 100 cm with only 1 volume percent you need 10 mm of infiltrated rainfall.

In reality the infiltrated rainfall will not immediately be spread over the whole rooting zone. In stead, the infiltrated rainfall will be concentrated in the upper part of the rooting zone effectuating higher soil moisture contents that may be higher than the critical soil moisture content. To simulate this water movement through the soil profile the balance method should be extended with more layers in the actual rooting depth. In summary, the scat method reaction on rainfall is more direct and sensitive to rainfall events while the balance method shows a slow, insensitive reaction.

Another reason for the different results between the both methods is that the scat method uses soil moisture contents which are based on the actual circumstances in the field. So after harvest, when the simulations still continue, the soil moisture contents based on the scat method are relatively high because of low the transpiration rates (no crop). So after harvest the soil moisture content in the scat method does not have any relation with evapotranspiration in the simulations.

4.3.2 Grid level

In general on grid level the balance method results indicates not only drought stress in Russia but also in the Ukraine (see Annex 8, fig. B). This drought stress calculated with the balance method occurs in the south, the east and also in the north of the Ukraine. The scat method only shows drought stress in the south of the Ukraine.

Fig. 6 presents the correlation between the results of both methods. Only those grid cells that have barley (see 3.6) are included (988 grid cells). The correlation is low (R-squared value of 0.14). Most of the values in fig. 6 are located above the x=y line. This indicates that the balance method calculates on average more drought stress than the scat method.

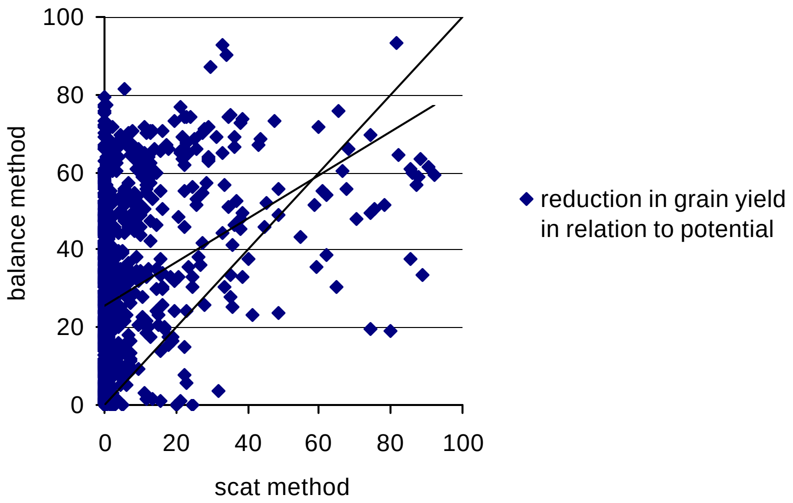


Fig. 6 Comparison of drought stress (water-limited reduction of grains in relation to potential) between scat method and balance method for 1994 in Russia and the Ukraine.

Detailed analysis of drought in the south simulated with the balance method

For more detailed analysis of the results we selected one grid cell (808) located in the Voronez region. This grid cell has respectively 65 and 2% drought stress for the balance method and the scat method. We deliberately have chosen a grid cell with a rainfall station inside (station 12534). This way we can assume that rainfall measured at this station also actually has fallen in this grid cell. For grid cells more distant from a rainfall station, such station is less representative for the grid cells because of the short distance spatial behaviour of rainfall.

In grid 808 six combinations of soil physical group and rooting depth occur. For all six combinations simulations has been carried out. Actually, the drought stress presented for grid 808 is the average drought stress of these six combinations, weighted for the area of each combination. To keep the analysis simple we concentrate on the combination of soil physical group 12 and rooting depth 110 cm with the largest area within grid 808. This combination covers almost 50 % of the total area of grid 808.

For this more detailed analysis we make use of graphs like the one presented in fig. 7. Fig. 7 shows time series of soil moisture based on the scat and balance method, the simulated critical soil moisture (depending on crop physiology and weather data) and the rainfall, all on decade base. In this example the soil moisture values are related to soil physical group 12. When soil moisture drops below the critical soil moisture water the assimilation rate and total biomass start to reduce: drought stress. Additionally the crop calendar is given, presented as two grey bars. They indicate from left to right: emergence and ripening.

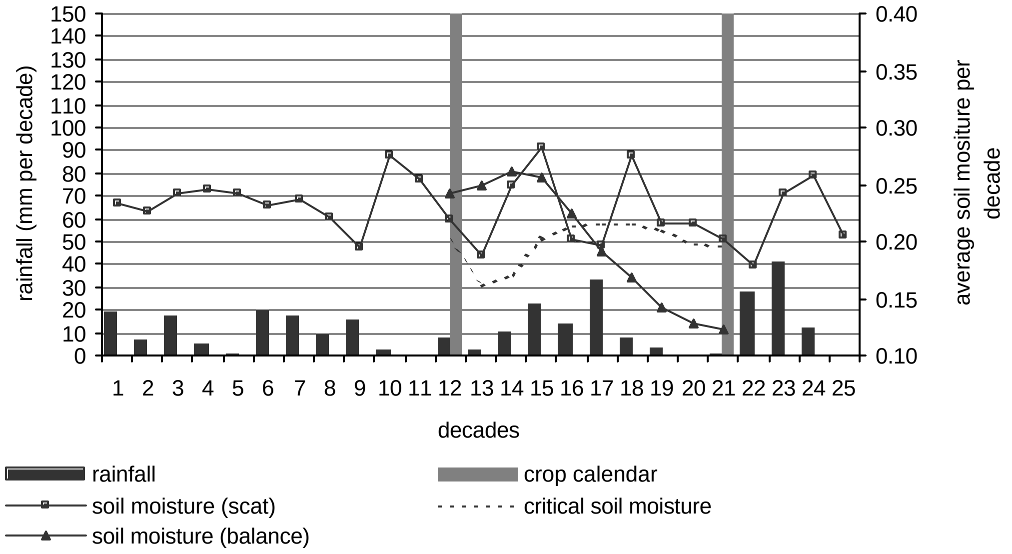


Fig. 7 Time series (1994) for grid cell 808 of soil moisture based on simulated water balance, ERS-scatterometer, combined with the simulated critical soil moisture, observed rainfall and crop calendar (from left to right emergence and ripening).

Fig. 7 shows clearly why the balance method simulated drought stress for grains. At decade 16 (start of June) the soil moisture of the balance method drops below the critical soil moisture and decreases until the end of the growing season. So, especially the grain filling phase suffers from this drought stress (see also 4.3.1).

Apparently, the rainfall in decade 17 (30 mm) can not stop the decreasing trend. This is remarkable because there is more than 3 mm per day available for evapotranspiration. In CGMS we simulate a barley crop with high potential crop production. It could be that the barley crops grown in Russia and the Ukraine have a lower potential crop production, resulting in a lower demand of water (lower evapotranspiration). For the scat method this possibly too high evapotranspiration is not relevant because in the scat method we already have the observed soil moisture so we do not need evapotranspiration to calculate soil moisture.

At sowing the soil moisture calculated by the balance method is between wilting point and field capacity. Before sowing the water balance is already simulated from the 1st of January to obtain a realistic estimate of the soil moisture at sowing. First part of the growing season the soil moisture of the balance method increases. This increase is the combined effect of two processes:

- rainfall recharges water in the soil profile and compensates losses due to transpiration and evaporation. Both transpiration and evaporation are low because it is early in the growing season (means relatively low temperatures and small plants).
- when the crop starts to grow the rooting depth extends to deeper soil layers. These layers all have relatively high soil moisture contents.

The scat method produces soil moisture contents during the growing season which in general follows the rainfall events. Only in July (decade 19, 20 and 21) it is remarkable that soil moisture does not decrease while there is almost no rainfall. Two possible explanations:

- the rainfall station misses an observation or the rainfall was very local and did not appear at the station. Actually, the 30th of June 1994 is missing for this station. Rain on this day could better explain the soil moisture pattern of the scat method. For the balance method the value for this day is replaced by a value of a more remote station. Suppose there was rainfall on the 30th of June and the replaced value was zero the balance method simulated a too low moisture content. It depends on the size of the rainfall whether this would have had impact on the simulations of the balance method.
- in decade 20 and 21 the fields are already harvested leading to low transpiration rates (no crop) and a small decrease of the soil moisture.

The soil moisture contents based on the scat method are above the critical soil moisture content, except for decade 16 and 17. The reduction of the assimilation rate due to the low soil moisture contents in these decades only results in very limited drought stress for the grains (2%). The magnitude of this yield reduction under this drought stress event should be investigated with help of more detailed field experimental data (see also 2.3.3 about the rough response to drought stress in CGMS).

4.4 Drought stress 1995

4.4.1 Oblast level

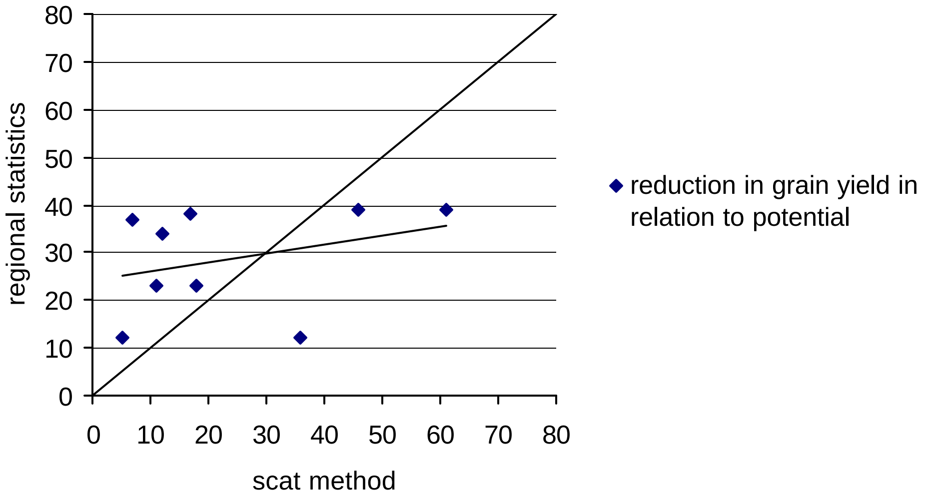
Compared to other years the regional statistics of 1995 have a relatively high drought stress ranging from 12 up till 39% (see Annex 9). The centre of the drought stress stretches diagonal from the south west to the north east (Belgorod, Voronez, Lipetsk, Tambov and Ryazan regions). On both sides of this belt there are regions with moderate drought stress (10-30%).

Drought stress calculated with the scat method and the balance method does not show a similar pattern as the regional statistics. According to both methods drought stress mainly occur in the south (Rostov, Voronez and Belgorod regions) and drought stress decreases with higher latitudes. Fig. 8 show a weak correlation between drought stress derived from both methods with the regional statistics.

Interesting to know is that later crops like sugar beets and potatoes do not have drought stress for the whole study area. So later in the growing season circumstances became better. Because our parameterised barley in CGMS has a too long growing season it could be that in both methods the north profited rain that in reality occurred after the growing season. This would especially effect the north. The north has lower temperatures and so it will take more days in the simulation to finish the grain filling stage (based on temperature sum). And more days means that the north more profit from wet days later in the growing season.

Both methods give more or less similar drought stress patterns on oblast level. Only in the Voronez and Belgorod region drought stress differs. The scat method gives for these regions a distinct higher value than the balance method.

For 1995 we can conclude that on average both methods generates similar soil moisture patterns in the study area. However, the calculated drought stress show clear differences with the regional statistics (the north).



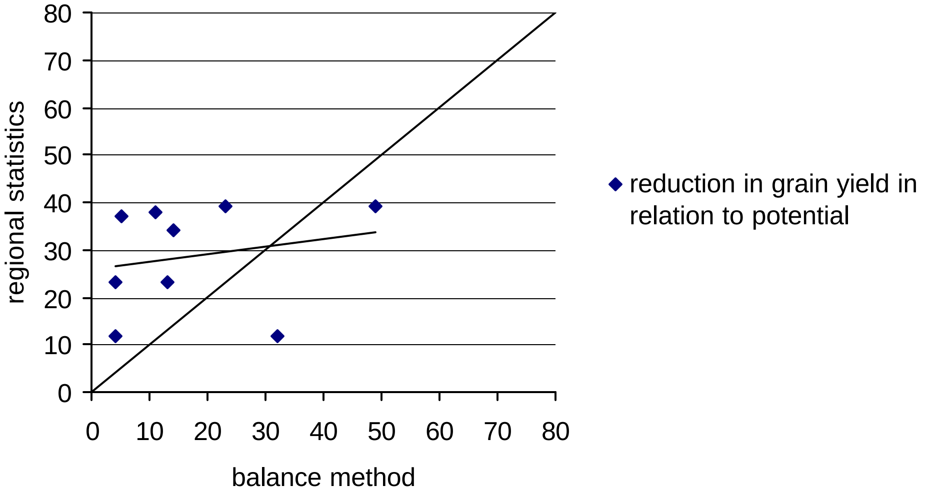


Fig. 8 Comparison of drought stress (water-limited reduction of grains in relation to potential) between scat method and regional statistics (top) and balance method and regional statistics (below) for 1995 in Russia.

4.4.2 Grid level

On grid level for Russia and the Ukraine both methods generate drought stress maps (Annex 10) which are not as similar as one should expect looking at the results on oblast level. The scat method shows less prominent drought stress at the southern area of the Ukraine. Furthermore the balance method calculates an area with drought stress in the north west of the study area.

Fig. 9 gives for all grids with barley the correlation between drought stress of both methods. The correlation between both methods (R-squared value of 0.30) is the highest in relation to the other years.

Position and curve of the fitted line

From the position and curve of the fitted line we can conclude that the scat method has more extreme drought stress values (between 80 and 100%). These extremes occur when the scat method starts around sowing with low moisture contents below the critical soil moisture content. The crop can not develop enough biomass (leaves) in the vegetative phase and will fail. In the balance method this does not happen so frequently. Apparently most grid cells start with a considerable amount of water in the actual and potential rooting zone. In case of early droughts this water prevents the crop from a total failure.

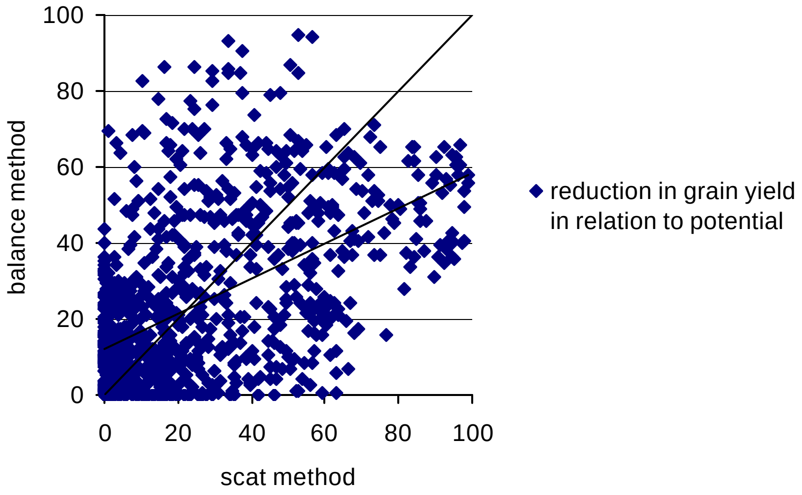


Fig. 9 Comparison of drought stress (water-limited reduction of grains in relation to potential) between scat method and balance method for 1995 in Russia and the Ukraine.

In the lower range of drought stress (less than 20%) the fitted line is on top of the x = y line which means that in this lower range the balance method simulates on average more drought stress than the balance method. For the balance method we observed that in many cases, when large rainfall events hold off, the soil moisture decreases during the growing season and drops below the critical soil moisture content at the second part of the growing season. Because drought stress happen at the end of the growing season the reduction in yield will be limited (no total crop failure). Part of these grid cells will have less drought stress with the scat method because this method reacts more sensitive to rainfall. The above described position and curve of the fitted line we can also observe for other years.

For a more detailed analysis of the results we selected the grid cell 808 located in the Voronez region and grid cell 1446 located in Mogilev region, north west of the study area. For grid cell 808 the scat method and balance method simulated respectively 95 and 62% drought stress for grain yield; for grid cell 1446 respectively 0 and 37%.

Detailed analysis: Voronez (grid cell 808)

First grid cell 808. Again we took the rainfall of station 12534 which is located within the grid cell and we concentrated on the combination of soil physical group 12 and rooting depth 6 (see 3.4) which covers almost 50 % of the total area of grid 808.

Fig. 10 shows clearly why both methods simulates drought stress. Soil moisture calculated with the scat method starts very low below the critical soil moisture. Then it even decreases in decade 13 and 14. Decade 15 has no SWI-values. In case of missing values CGMS uses the last known value. This is the value of May the 14th 1995 which was very low (0.78 on a scale from 0 to 100). Thus for the last two weeks in May and the first five days in June CGMS used this extreme low value nearby wilting point. This caused a total failure (95%) of the grain production. The highest leaf area index of barley was 0.18 in the first decades. Grid 808 is not the only grid cell with missing values for May. All grids cells around grid cell 808 (southern part of Voronez and northern part of Rostov) have missing SWI values for the second half of May.

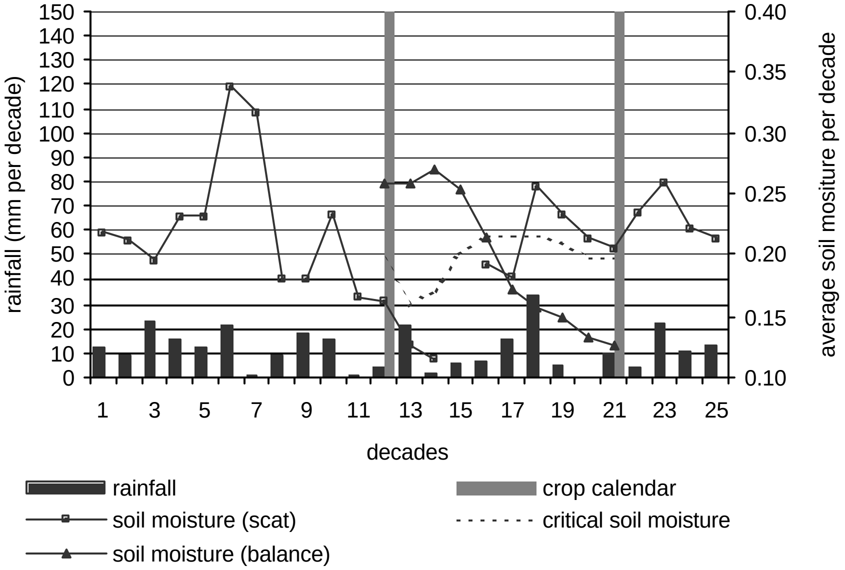


Fig. 10 Time series (1995) for grid cell 808 of soil moisture based on simulated water balance, ERS-scatterometer, combined with the simulated critical soil moisture, observed rainfall and crop calendar (from left to right emergence and ripening).

Probably the drought stress would have been less when the scat method had used real values for the second half of May. But the low values in the first two decades (13 and 14) (leading to low leaf area indices) already points to important drought stress also for the final grain yield. These low values at the start of the growing season are remarkable and probably unreal.

These low soil moisture values of the scat method at the start of the growing season occur in many other grid cells. An explanation for the low soil moisture values are the extreme low values of m_s that occur when soil is frozen and covered with wet snow. These low m_s -values contribute to low SWI-values. A possible solution could be to set the m_s -values to 100% during the cold season (frozen soils, snow conditions). Of course only for areas where frozen and snow conditions occur.

According to the balance method the soil moisture around sowing is clearly above the critical value. This soil moisture is based on simulation of the water balance from January 1st 1995. All though rainfall in March and April is not high (approximately 1 mm per day) also the evaporation is low because of low temperatures and low radiation. Thus it seems reasonable to start with soil moisture contents in the soil profile that are well above the critical value.

But also simulation of the water balance before sowing is not reliable under frost and snow conditions. Therefore we would need to use a complicated and high input demanding model with functionality to simulate soil moisture behaviour under such conditions.

So, for both methods the initial moisture content at sowing after a period of frost and snow is unreliable. A first estimate in a next study could be to set the soil moisture around field capacity if there is a substantial amount of snow that will melt. Besides that the typical m_s-pattern before the growing season could be used to estimate the sowing date. The typical pattern is as follows: low under frozen soils, fluctuating under thawing/freezing conditions and decreasing when it start to get warmer. See for examples fig. 11 and 12.

In general (and especially areas with no frost or snow conditions) we may improve the conversion from m_s to SWI values. The currently applied conversion into SWI (indicates relative soil moisture) assumes a water balance in which rainfall disappears via evapotranspiration, percolation subsurface runoff at the <u>same</u> rate throughout the year. It is more likely that rainfall in early spring will stay longer in the soil profile than in the middle of the summer because evapotranspiration is much lower in early spring. When the conversion of m_s into SWI takes this yearly variation into account the SWI-value will be higher in spring than in summer.

Of course this only works when the m_s -values have realistic values throughout the year thus for areas without frost and snow. Besides, the conversion can be improved by implementing the spatial variation in soil hydro-physical properties. These properties determine how fast water will percolate through the soil to groundwater or surface water. In summary: the current conversion of m_s into SWI should be changed to include spatial variation in soil hydro-physical properties and within year variation of evapotranspiration. The latter could be established by the introduction of a seasonal factor on the m_s signal.

The course of soil moisture in fig. 10 based on the balance method during the growing season looks similar as in fig. 7. The soil moisture content at the start of the growing season is below field capacity but distinct higher than the critical soil moisture. After a small increase in decade 14 the soil moisture starts continuously decreasing until the end of the growing season (see 4.3.2 for more explanation). In the second part of the growing season the soil moisture is far below the critical soil moisture content.

Fig. 10 gives a good example of the different behaviour of the two methods. The rainfall in decade 18 (34 mm) causes a large increase of the soil moisture based on the scat method and setting the level above the critical soil moisture content. In contradiction with the scat method, the balance method does not show a increase in the soil moisture content. The rainfall event only causes a smaller average decrease of the moisture content in decade 18. Apparently all rainfall in decade 18 disappeared through runoff, evaporation and transpiration, leaving nothing to increase the soil moisture content.

Detailed analysis: Mogilev (grid cell 1446)

Grid cell 1446 located in Mogilev region, in the north western part of the study area has no drought stress for the scat method and high drought stress for the balance method. Fig. 11 explains these results.

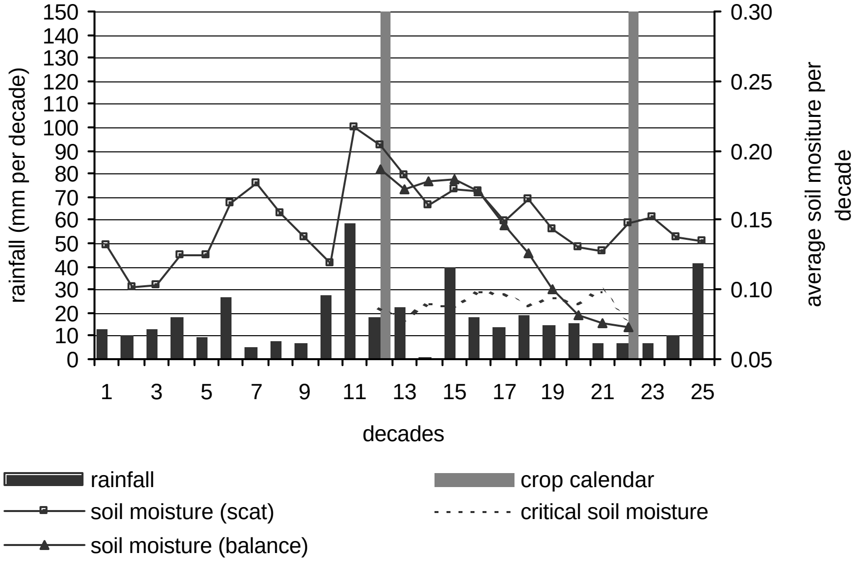


Fig. 11 Time series (1995) for grid cell 1446 of soil moisture based on simulated water balance, ERS-scatterometer, combined with the simulated critical soil moisture, observed rainfall and crop calendar (from left to right emergence and ripening).

First half of the growing season both methods show same levels of soil moisture. Again the balance method simulates a similar course of soil moisture compared to the other grid cells presented before: first a small increase followed by a continuously decrease. Rainfall with an average of less than 2 mm per day is not sufficient for the crop growth therefore the crop also uses water from the soil profile leading to lower soil moisture contents. After the crop has used more than 100 mm water from the soil profile, the soil moisture of the balance method drops below the critical soil moisture content causing the drought stress in the grain yield.

Soil moisture based on the scat method follows the rainfall events clearly. On average the soil moisture also decreases towards the end of the growing season, but this decrease is much smaller compared to the balance method. The soil moisture never drops below the critical soil moisture so no drought stress occurs.

To judge which of both methods is more conform reality one should have data about the actual drought stress in this grid cell. For example data of experimental fields. Such data are available for the period 1995 and later at the Agrometeorological Institute of Russia. For some stations for 1995-1998 experimental field data is available at Rosgidrometcenter.

Detailed analysis: Tula (grid cell 1612)

One of the main differences between both methods and the regional statistics is the large drought stress in the north according to the statistics. We selected one grid cell (1612) in the north (Tula region) with a rainfall station (12597) within the cell. Fig. 12 shows the soil moisture contents and the rainfall for this grid cell.

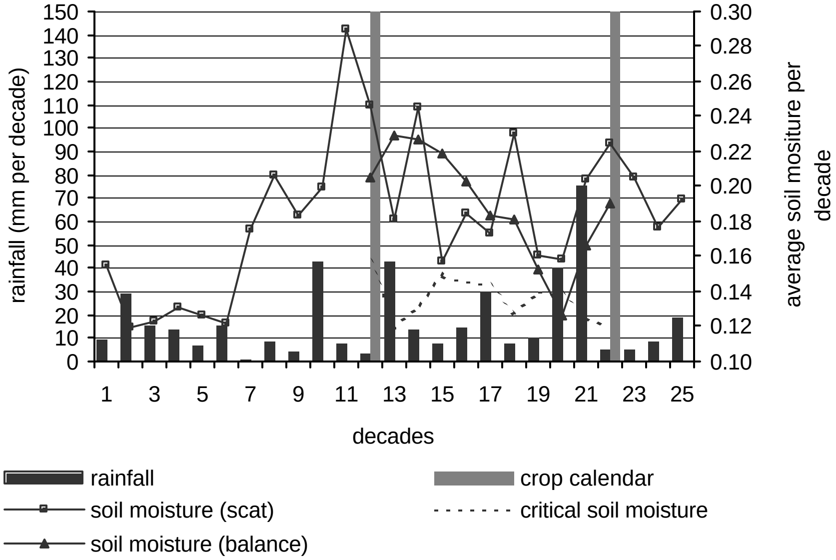


Fig. 12 Time series (1995) for grid cell 1612 of soil moisture based on simulated water balance, ERS-scatterometer, combined with the simulated critical soil moisture, observed rainfall and crop calendar (from left to right emergence and ripening).

The balance method simulates a decreasing soil moisture content until the end of decade 19. It just drops below the critical soil moisture content. Decade 20 and 21 have large amounts of rainfall (on average 4 to 7 mm per day). This is enough to increase soil moisture content high above the critical soil moisture content. The drought stress for grains is almost zero (0.8%). The scat method shows a more fluctuating soil moisture content compared to the balance method following the temporal variation in rainfall. Around decade 19 the soil moisture calculated with the scat method is also low and reaches the critical soil moisture content. The rainfall events in decade 20 and 21 cause a large increase of the soil moisture content based on the scat method.

It is clear that the rainfall in second half of July facilitates recovery of drought stress in both methods. Probably in reality the barley did not profit this rainfall because the growing season already ended. CGMS uses a barley variety with a too long growing season (see 4.3). This explains probably why the statistics give drought stress for the north and both methods do not.

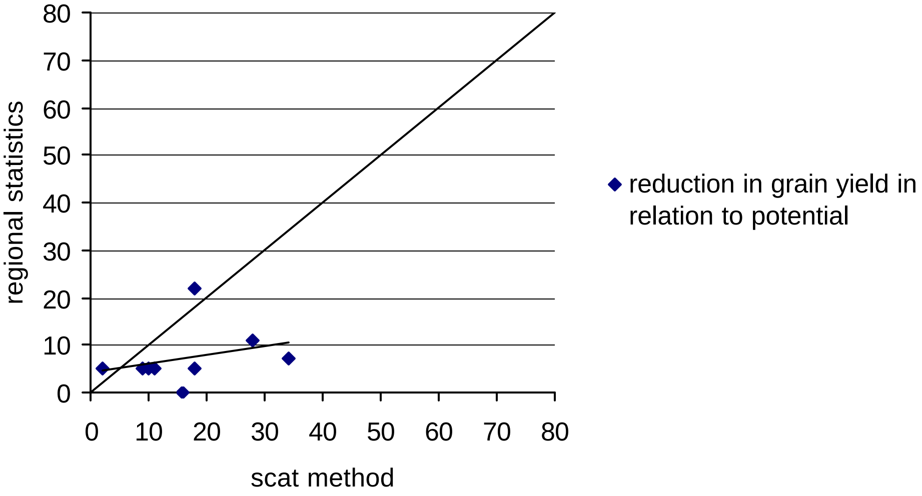
4.5 Drought stress 1996

4.5.1 Oblast level

According to the regional statistics drought stress occur in the Orel region (11%) and the Lipetsk region (22%) (see Annex 11, fig. C). The other regions all have drought stress less than 10%. It is difficult to explain the drought stress, presented by the regional statistics, through rainfall patterns. In relation to other oblasts, Orel and Lipetsk regions do not have the lowest rainfall (see Annex 2) during May, June and July. The more south east situated Voronez region has lower rainfall amounts but only 5% drought stress. An average lower water retention capacity in the Orel and Lipetsk region than in the Voronez region would explain such a difference but the available soil water in Annex 3 does not support such an explanation.

Except for Orel and Lipetsk regions the scat method also give drought stress for Tula, north of these two regions, and Kursk, Voronez and Rostov, south of these two regions. The latter region has the most severe drought stress calculated with the scat method. These differences in drought stress are also illustrated by fig. 13. There is some positive correlation between drought stress, calculated with the scat method and the regional statistics but except for the Lipetsk region all values of the scat method are too large in comparison with the regional statistics (values are mainly below the x = y line).

Also the balance method shows drought stress which occurs in the middle and the south of the study area, but there are differences in comparison with the scat method, though. The balance method does give drought stress (34%) for Belgorod region and slight drought stress (3%) for the Orel region whereas the scat method gives respectively slight drought stress (9%) and severe drought stress (28%). The slight drought stress in the Orel region is only based one rainfall station. It is possible that the rainfall recorded at this rainfall station was more local and should not characterise the whole region as wet. To validate this theory we would need more rainfall stations.



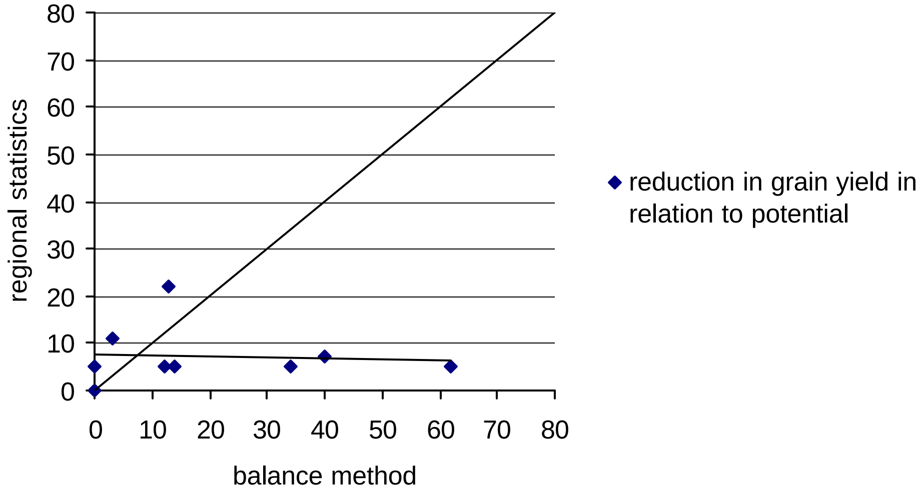


Fig. 13 Comparison of drought stress (water-limited reduction of grains in relation to potential) between scat method and regional statistics (top) and balance method and regional statistics (below) for 1996 in Russia.

Furthermore the balance method gives more drought stress in the Voronez and Belgorod region compared to the scat method and the regional statistics.

The drought stress calculated with the balance method does not give any relation with the regional statistics (fig. 13). In summary: both methods differ from the regional statistics but also differ from each other.

4.5.2 Grid level

The scat method simulates drought stress mainly in the Orel region, the west of the Lipetsk region and the east of the Kursk region (Annex 12). Compared with drought stress based on the regional statistics (Annex 11) this area covers nicely the drought stress regions in these statistics. The drought stress in the Voronez region, simulated with the scat method, is due to another area with drought problems which has it centre in the Rostov region.

Interesting question is why the statistics does not show any drought stress in the Rostov region while both methods indicate severe drought problems. This would be an interesting region/year for a more detailed study in future.

For the Voronez region one would expect drought problems because of the monthly rainfall sums (see Annex 2). The balance method, based on this rainfall, does show the highest drought stress in this region. This drought stress area is not limited to Voronez but crosses the borders to Belgorod, Lugansk and Rostov region. Because the monthly rainfall sums are based on several stations it is likely that the extensive area of relatively low rainfall is reality. More detailed study may explain why both methods differ for this region.

Fig. 14 shows the relation between the simulated moisture content of the scat method and the balance method. Most of the points are located above the x=y-line which means that the balance method simulates more drought stress.

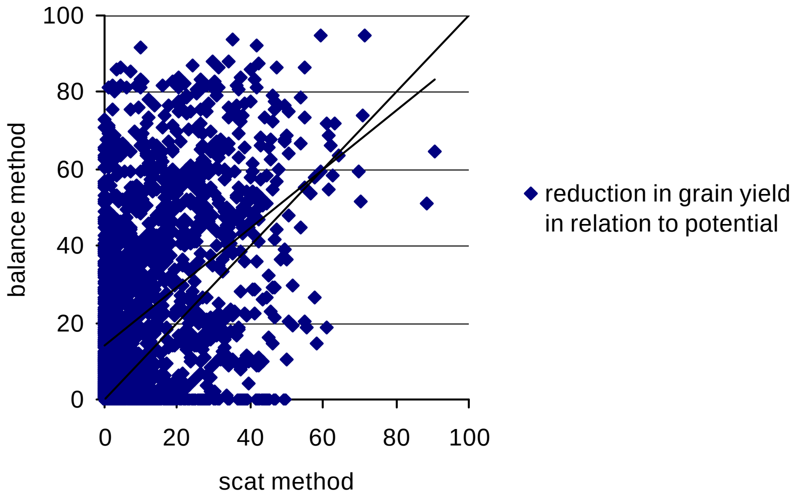
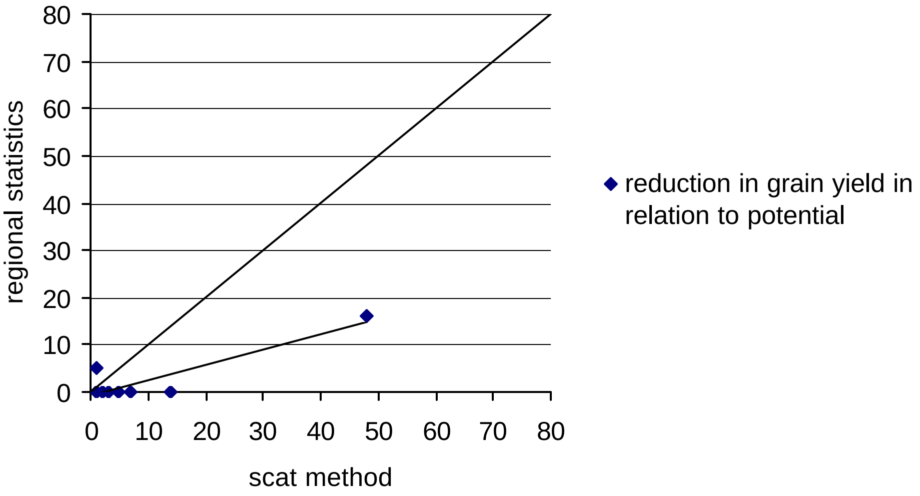


Fig. 14 Comparison of drought stress (water-limited reduction of grains in relation to potential) between scat method and balance method for 1996 in Russia and the Ukraine.

4.6 Drought stress 1997

4.6.1 Oblast level

According to the regional statistics 1997 is a year without major drought stress (see Annex 13). Only the Rostov region has a reduction of 16% of the grain yield caused by drought. All other regions have a reduction of less than 10%. Results of the scat method look similar. The Rostov region has the highest drought stress: 48%. All other regions have drought stress less than 10% except for the Belgorod region with 14%.



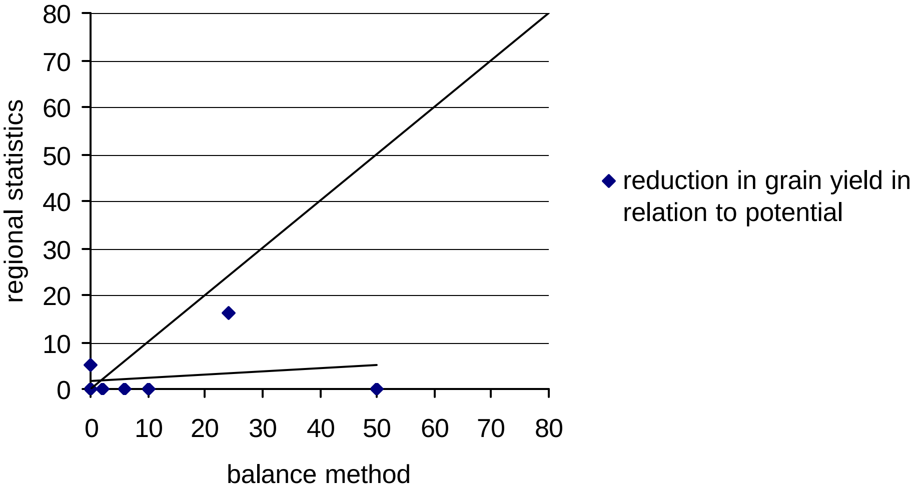


Fig. 15 Comparison of drought stress (water-limited reduction of grains in relation to potential) between scat method and regional statistics (top) and balance method and regional statistics (below) for 1997 in Russia.

The correlation between the scat method and the regional statistics is shown in fig. 15. The R-squared value of 0.79 indicates a good relation. However the importance of this measure is limited because most of the regions have so little drought stress that variation within these values is more due to uncertainties than to some realistic drought pattern.

Also the balance method shows only yield reduction due to drought stress in the south: the Rostov and Voronez region. The drought stress in the latter region is not given by the scat method and the regional statistics. The low monthly rainfall sums in the Voronez region (see Annex 2) explain why the balance method simulates drought stress. For all years the balance method simulates the highest drought stress in this region. This does not correspond with the results of the scat method and the regional statistics. Therefore it is advisable to check the rainfall data for this region. May be there are systematically errors in the observations or post-processing of the rainfall data.

The remarkable difference for the Voronez region leads to weak relation between the balance method and the statistics (low R-squared value of 0.05).

4.6.2 Grid level

On grid level the scat method simulated four areas with drought stress: a large area in the Rostov region, two areas in the Ukraine (Donetsk and Khersonska) and a small area in the Belgorod region (Annex 14). Major difference between the scat method and the balance method is that the balance method calculates the drought stress in Russia more to the north in the Voronez region. In the Ukraine the Khersonska region has grain yield reduction in both methods. The drought stress in the south west of the Donetsk region is less in the balance method.

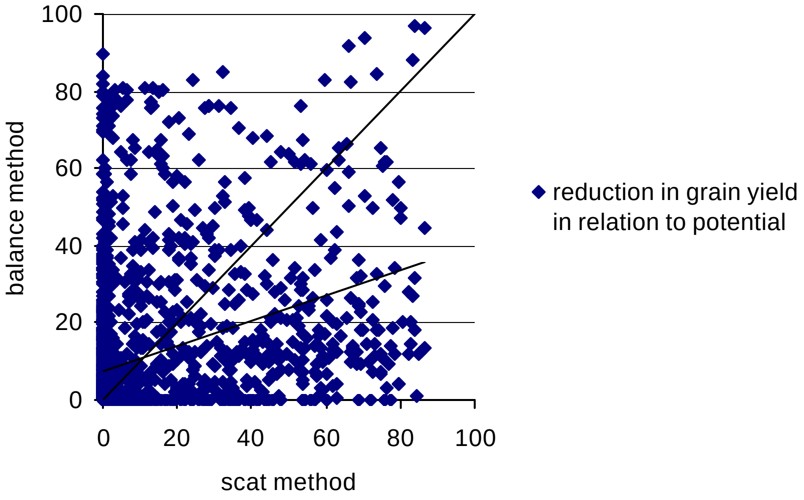


Fig. 16 Comparison of drought stress (water-limited reduction of grains in relation to potential) between scat method and balance method for 1997 in Russia and the Ukraine.

The correlation between both methods is low (R-squared value of 0.11) (fig. 16). Remarkable are the extremes like high drought stress for the balance method around 80% and no drought stress for the scat method and vice versa. It would be interesting to examine these large differences; of course not only for 1997 because we see these extremes also in other years (especially in 1994 and 1996 where the balance method on average has larger drought stress than the scat method). Grid cells with these large differences in combination with more detailed statistics of experimental plots (drought stress, rainfall, crop variety, crop parameters, soil data) could explain the differences and reveal unknown artefacts of the method and/or input data.

4.7 Drought stress 1999

In 1999 we used the scat method in CGMS to monitor the drought stress during the growing season. Starting from sowing date for each decade drought stress is calculated. Annex 15 shows the drought stress at the end of May (decade 15), the end of June (decade 18) and the end of July (decade 21). At the end of decade 15 according to the scat method no drought stress occurred in the whole study area. One month later the situation is completely changed. A large area, covering parts of the oblasts Rostov, Voronez, Belgorod, Kursk, Orel, Lipetsk, Tambov and Ryazan, has severe drought stress. The situation is less dramatic in the Ukraine with smaller areas of drought stress wide spread over the Ukrainian part of the study area.

At the end of July the drought stress situation is similar to the one at the end of June. But there are small differences. The drought area in the south of the Voronez region and the Rostov region becomes smaller. This in contradiction to the area around the Kursk, Orel and Lipetsk region that becomes larger. In the Ukrainian part of the study area there are no remarkable changes. So the drought problems in the study area do not diminish but move a little bit from the south east to the middle.

Finally, at the end of the growing season, Annex 15 shows the drought stress per oblast. Compared to 1994-1997 the drought stress based on the scat method in the Russian part of the study area is most severe in 1999. All regions have drought problems. The regions Kursk and Lipetsk have the biggest problems with an average reduction of the grain yields of more than 50%. The lowest drought stress can be seen in the regions Tula, Ryazan, Tambov and Voronez. Still these regions have reductions between 30 and 40%.

Up till now we do not have official data about yield statistics in 1999. Neither we simulated the drought stress with the balance method because we did not have rainfall data. Especially 1999 seems to be interesting to compare the scat method with regional statistics and the balance method.

5 Conclusions

5.1 Method - general

- CGMS has been extended with new functionality to calculate soil moisture contents based on the ERS-scatterometer.
- The response to drought stress in CGMS is rough and should be improved. In reality damage from drought builds up more gradually (better water consumption strategy or by getting water from the subsoil below the main rooted zone). The description of death of leaves due to drought stress could be improved as well. In CGMS it is assumed that here is accelerated decay leading to immediate death of the eldest leaf age classes, but it does not affect the ageing of younger leaves. Finally, the effect of drought stress on yield depends on crop stage. Many crops are more sensitive to stress during a critical period such as flowering. This is not included in CGMS.

5.2 Scat method

- In areas with frozen soils and snow the scat method has often with very low soil moisture contents at the start of the growing season. The low soil moisture values are caused by extreme low values of m_s that occur when soil is frozen and covered with wet snow. These low m_s -values contribute to low SWI-values. Also the balance method simulates unreliable soil moisture contents in such situations because frost and snow are not modelled in CGMS.
- In the conversion from m_s to SWI the scat method assumes that rainfall in the soil profile disappears via evapotranspiration, percolation subsurface runoff at the same rate throughout the year. It is realistic to assume lower evapotranspiration rates in spring which will lead a better estimate of the water storage in the soil profile at sowing. Also the scat method assumes the same soil hydrological properties throughout the whole area. These properties (and thus the spatial variability) are important to determine how fast rainfall will percolate through the soil profile.
- The conversion of SWI into an absolute soil moisture content is based on well drained loamy soils and does not vary for different soils. For coarse sandy soils the highest SWI value could be more towards field capacity than towards saturation and vice versa for a clay soil under wet conditions (bottom of a valley).
- In areas with ground water levels nearby the rooting zone ground water can have significant influence on the soil moisture in the rooting zone. In such a case the SWI (only based on rainfall) is less suitable as an indicator for the average soil moisture in the rooting zone. However, those areas are less interesting for monitoring drought stress.

5.3 Data

- A new database for Russia and Ukraine (only parts of countries that are in the study area) has been set up covering all relevant aspects for simulating drought stress for the years 1994 - 1999 (data like SWI, soil, weather, crop calendar and parameters, land cover, yield statistics).
- The crop parameters of barley were not tuned for the Russian / Ukrainian study area. This has lead to a too long growing season in the simulations (on average two weeks longer). The length of the growing season is important because differences in the length could mean for example that the crop misses or profits a late rainfall event at the end of the growing season.
- The barley crop we used has a relatively high potential crop production. It could be that the barley grown in Russia and the Ukraine has a lower potential crop production, resulting in a lower demand of water (lower transpiration) and thus lower drought stress. This is only relevant for the balance method because transpiration is used to determine soil moisture.
- Data about sowing dates is too limited. Some years (1994 and 1996) are missing. For these years long term average sowing dates are used. For 1994 and 1996 the network of observations is not regularly spread (no observations in the Ukraine) resulting in bad estimates for the Ukraine. Sowing dates derived from the ERS-scatterometer would solve this problem.
- A weak point of the weather driven water balance (balance method) is the need for an extensive network of rainfall stations. Especially in our study area rainfall has a high spatial variability in summer. A more dense network of rainfall stations could improve the results of the balance method.
- To simulate drought stress in the current year (1999) we used the long term average sowing date. Because it is the current year we can not make use of sowing dates statistics. Sowing dates derived from the ERS-scatterometer would solve this problem.
- To monitor drought stress in the current year (1999) with the scat method we still need weather data like temperature, irradiation, wind speed, vapour pressure for the calculation of growth development and evapotranspiration. Because this data was not available in real time we had to use long term average values. Of course it would be better to have real time data.

5.4 Validation of the scat method (1994 - 1997)

- For two of the four years (1994 and 1997) the scat method gives drought stress values on oblast level that are similar to the regional statistics. For 1995 the scat method give more drought stress in the north and for 1996 the scat method gives more drought stress in the south.
- A major part of the differences between both methods (scat and balance) and the regional statistics can be explained by the quality of input data (crop variety, sowing dates, soil moisture under snow/freezing conditions) and limitations in

methods which both can be improved. Table 3 and 4 give overviews of items that causes differences between both methods and regional statistics.

Table 3 Explanations for differences between scat and balance method

	Scat method	Balance method
1.	-	Insensitive for small rainfall events because of simple 2-layer model.
2.	Initial soil moisture unreliable in case of snow and frost conditions (SWI signal unrealistic fluctuations)	Initial soil moisture unreliable in case of snow and frost conditions (not modelled in CGMS).
3.	SWI (thus soil moisture) follows real cropping season which is shorter than simulated cropping season.	Soil moisture is simulated in CGMS and thus follows the simulated cropping season.
4.	-	Potential yield (and thus water demand) of crop variety too high resulting in too low soil moisture contents.
5.	Incomplete SWI data	Incomplete rainfall data
6.	Conversion of m_s in SWI is not specified for different hydro-physical properties and seasonal variations in evapotranspiration	-
7.	Conversion of SWI in absolute soil moisture is not specified for different soils	-

Table 4 Explanations for differences between scat method and regionalstatistics

	Scat method	Regional statistics
1.	Estimation of soil moisture (initial soil moisture under snow and frost conditions; incomplete SWI-data; different conversions from m_s to SWI and SWI to absolute soil moisture)	-
2.	Too long cropping season due to unsuitable crop variety	
3.	Shortcomings in drought stress formulation in CGMS	
4.	Uncertainties in sowing dates	
5.	Aggregation of drought stress from grid cells to oblasts	
6.	-	Reliability statistics (expert judgement of drought stress)

- The balance method simulates in most cases only drought stress at the end of the growing season. First part of the growing season the balance method profits from the water storage in the soil profile. In the second part the soil moisture drops below the critical soil moisture contents. At that time only large rainfall events can set the soil moisture back above the critical soil moisture content while in the scat method smaller rainfall events lead to an increase of the soil moisture.
- Grid cell 1446 located in Mogilev region is an example where the scat method and balance method differ. Both methods simulate decreasing soil moisture contents during the growing season. Only the soil moisture content calculated

with the balance method drops below the critical soil moisture content. It is difficult to judge which of both methods is more conform reality. More detailed study and data are needed.

5.5 Monitoring 1999

- In 1999 we used the scat method in CGMS to monitor the drought stress during the growing season. At the end of decade 15 (end of May) according to the scat method no drought stress occurred in the whole study area. One month later the situation is completely changed. A large area in Russia has severe drought stress. The situation is less dramatic in the Ukraine. At the end of July the drought problems in the study area do not diminish but move a little bit from the south east to the middle.
- Compared to 1994-1997 drought stress based on the scat method in the Russian part of the study area is most severe in 1999. All regions have severe drought problems.

6 Recommendations

6.1 Method

- A first estimate for the initial soil moisture content at sowing in areas with frost and snow is to set the m_s -values to 100% during the cold season (frozen soils, snow conditions). This way the extreme low values of m_s that occur when soil is frozen and covered with wet snow are skipped and it assumed that the soils start wet (between field capacity and saturation) which seems a realistic assumption for regions with melted snow / low evaporation.
- For areas without frost and snow conditions we may improve the estimate of the initial soil moisture content by diversifying the conversion from m_s to SWI values. The currently applied conversion into SWI assumes a water balance in which rainfall disappears via evapotranspiration, percolation subsurface runoff at the same rate throughout the year. It is more likely that rainfall in early spring will stay longer in the soil profile than in the middle of the summer because evapotranspiration is much lower in early spring. When the conversion of m_s into SWI takes this yearly variation into account the SWI-value will be higher in spring than in summer.
- The conversion from m_s to SWI should take the variability in soil hydrological properties into account because these properties determine how fast rainfall will percolate through the soil profile.
- The response to drought stress in CGMS can be improved. One improvement is to increase the physiological age of all leaves in response to drought stress in stead of only the eldest leaf age classes.
- For the balance method the infiltration of rainfall through the soil profile could be improved. The water balance in the balance method should be extended with more layers in the actual rooting depth. This will make the balance method more sensitive to rainfall events because rainfall will be more concentrated in upper part of the soil profile in stead of being spread of through the whole soil profile.

6.2 Data

- To get real time estimates of sowing dates for the current year these dates should be derived from the ERS-scatterometer. Also for the other years (1994-1998) it would be interesting to compare sowing dates derived from the ERS-scatterometer with observed sowing dates and to apply both kind of sowing dates in the simulations.
- Improve the drought stress simulations by using typical Russian and Ukrainian varieties of barley (or other cereals). Especially temperature sums and the potential production level can be improved.

- To monitor the drought stress in the current year with the scat method it would advisable to have real time data about temperature, irradiation, wind speed, vapour pressure of the synoptic stations.
- Areas with groundwater influence on the crop production should be excluded from the study area. The crops in these areas have less drought stress, if any, and besides the soil moisture contents in the rooting zone are not well determined by the scat method because the scat method is only based on rainfall.

6.3 Validation of the scat method (1994 - 1997)

- Carry out new simulations with the scat method and the balance method with improvements regarding input data and methodological aspects (see above). Compare these simulations also with regional statistics for 1998 and the Ukrainian part of the study area.
- Select a few grid cells or oblasts where remarkable, unexplained differences are between the scat method and the balance method and the yield statistics for certain years in 1994 - 1999. For these situations more data should be selected e.g. yield statistics of experimental plots, soil moisture observations, detailed rainfall etc. A more detailed analysis could explain the differences and reveal unknown artefacts of the method and/or input data. Interesting areas are: Mogilev region (grid cell 1446) in 1995; Rostov region in 1996; Voronez region in 1996; Voronez region in 1997.

6.4 Monitoring 1999

- Because of the severe drought stress in 1999 (simulated with the scat method and also known from the alarming news during the growing season) this year is especially interesting to compare the drought stress of the scat method with regional statistics and the balance method.

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Annex 1 The weather interpolation in CGMS

Introduction

The CGMS method for interpolation of weather data was developed for estimating daily values of seven weather variables on the centres of about 1400 grid cells over the European Union, using daily station values. The number of meteorological stations with sufficient data varied over the years from 200 to 600, and also spatial density of the station network varied over the countries. A universally applicable algorithm was required with objective criteria for station selection and calculation of interpolated values, fully automated, without requiring interactive choices.

The algorithm was developed stepwise by testing and validation in several test regions. The validation was done with the leave-one-station-out method, and consisted in comparing observed station data with interpolated values at that station. The conclusions from the first test regions were, that with regard to number of stations, the use of two or more stations gave better results than substitution from one station, except for rainfall. Other exceptions occurred where one station is situated at very short distance, and near the edges of the continent and on remote places. The use of more than four stations did not give additional improvement.

There were sometimes country-specific differences, and similarities in weather data values were found for stations in coastal zones and for stations in high altitude zones. There were no seasonal differences in performance of interpolation algorithms. This called for the use of a variable number of stations with a maximum of four, and to take into account the differences in site characteristics with respect to proximity, configuration, elevation, distance to coast, and climatic barriers.

Based on these results, an interpolation algorithm was developed for the variables: minimum temperature, maximum temperature, daily global radiation, cloud cover, or SSD sunshine duration, air humidity, rainfall and wind speed.

Interpolation of rainfall

For interpolated rainfall it is required that the temporal pattern is realistic in terms of number of rainy days and amount of rainfall, because in the simulation of the soil water balance the effect of every day a little shower is different from one big shower per week. When rainfall data from several surrounding stations would be averaged, the rainfall peaks are levelled off and the number of rainy days increases. Therefore the rainfall of the most similar station is used.

The criteria for similarity are expressed in terms of proximity, difference in altitude and in distance to the sea, and position relative to climatic barriers. The similarity between interpolation point i and station m is quantified by means of a difference score ($S_{i,m}$), which is conceived as a measure of meteorological distance and defined as follows (Van Diepen and Van der Voet, 1998):

$$S_{i,m} = \Delta d_{i,m} + a \cdot \Delta a_{i,m} + \Delta c_{i,m} + \Delta b_{i,m}$$

$S_{i,m}$: meteorological distance between station *m* and interpolation point *i* [km]

$Dd_{i,m}$: horizontal (Euclidian) distance between station *m* and interpolation point *i* [km]

$Da_{i,m}$: absolute differences in altitude between station *m* and interpolation point *i* [m]

a : weighing factor for $Da_{i,m}$ (= 0.5) [$\mathrm{km.m}^{-1}$]

$Dc_{i,m}$: absolute differences in corrected distance to coast between station *m* and interpolation point *i* [km]

$Da_{i,m}$: presence of climate barrier between station *m* and interpolation point *i* [km]

The station with the lowest score is identified as the most similar station, and the optimum one to be used for substitution of rainfall data. When station and interpolation point are on the same location the score is zero. The correction for elevation differences (α) has been set at 0.5 km per m which is based on the assumption that 100 meter difference in elevation is equivalent to 50 kilometre distance. Finally, the score is corrected for differences in distance to the coast between the interpolation point and the weather station, illustrated in the following scheme (table 1).

Table 1 The effect of distance to the coast on the final score (km) illustrated with interpolation points in a row at increasing distance from the sea, both for a coastal station and an inland station (> 200 km from the sea).

Real distance from i-point to the coast (km)	Addition to final score (km) of coastal station	Addition to final score (km) of inland station
0	0	100
50	50	50
100	75	25
200	100	0
300	100	0

The maximum value of this corrective increase in meteorological distance is 100 km, e.g. this is added to the true distance between a station on the coast line and an interpolation point situated at more than 200 km from the sea. Note that only when station and interpolation point are located within 200 km from the generalised coastline the meteorological distance can be increased by a correction for differences in distance to the coast. The coastal influence on the score is shown in fig.1.

As climatic barriers at the scale of Europe only the Alps and the Pyrenees were identified. The difference-score is increased with a value of 1000 when station and interpolation point are situated at opposite sides of these pronounced climatic divides. The effects of less important mountain ranges could not be clearly assessed with the data available. For making it operational, it requires a sharp boundary over the grid lines.

Stations at a distance of more than 400 kilometres from the interpolation point are excluded in the calculation of the score. They cannot be used for the interpolation. Only in areas with a very limited number of stations this can lead to a situation that no stations are chosen for the interpolation point.

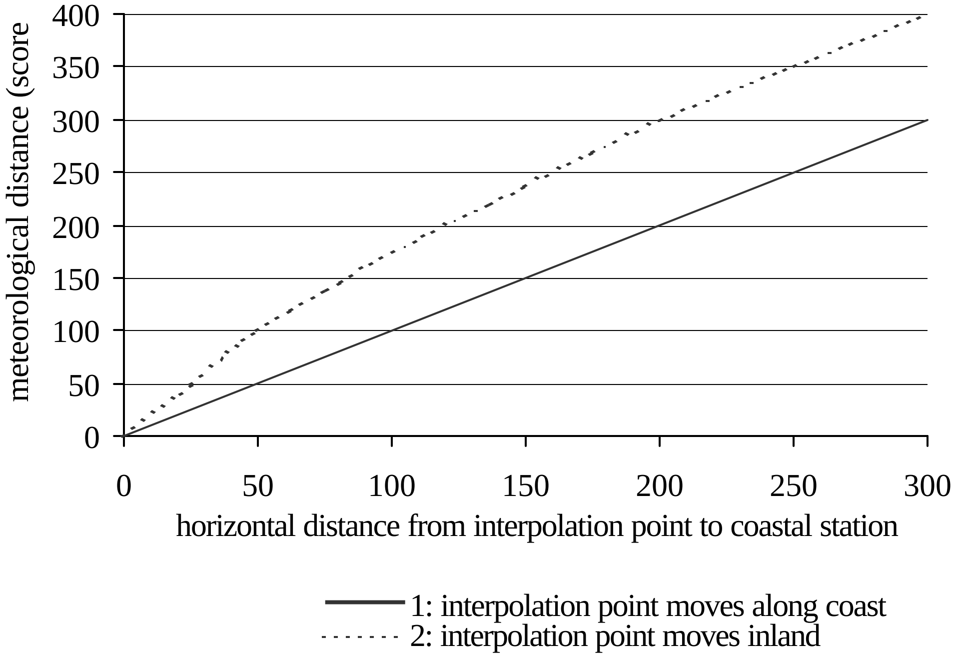


Fig. 1 The meteorological distance (score) between interpolation point and coastal station for two situations: 1) interpolation point moves along the coast and 2) interpolation point moves inland.

Interpolation of temperature, radiation, air humidity and wind speed

As explained, rainfall is estimated using one station. The values for the other variables (temperature, radiation, air humidity and wind speed) are estimated by averaging the values of a selected set of stations, surrounding the centre of the grid cell. The selection criteria for this set of stations are an extension of the criteria for the identification of the most similar single station for rainfall. The extension includes a measure for the configuration of stations around the interpolation point, i.e. the regularity of the pattern in which the selected stations are arranged around it, and a rule to influence the number of stations in the set.

The optimum set of stations is identified on the basis of a suitability score. For each possible set this score is calculated and the set with the lowest score is selected. For a set (‘c’) of stations M_1 to M_n (‘n’ has maximum of 4) and interpolation point i, the suitability score ($U_{i,c}$) is defined as follows (Van Diepen and Van der Voet, 1998):

$$U_{i,c} = \frac{1}{n} \sum_{m=1}^{n} S_{i,m} + \Delta g_{i,c} + b \cdot S_{\min,\ i}$$

$U_{i,c}$: suitability score of the set stations c for interpolation point i [km]

c : set of 1 up till 4 stations surrounding interpolation point i [-]

n : number of stations in set c [-]

$Dg_{i,c}$: distance between geographic centre of gravity of a given set of stations c and interpolation point i [km]

$S_{min,i,}$: lowest meteorological distance between certain station and interpolation point i [km]

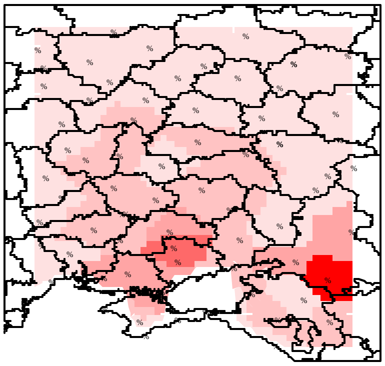
b : correction term for number of stations that appears in set c (for a single station b = 0.5, for a set of two stations b = 0.2 and for more than two stations b = 0) [-]

The procedure starts by identifying the seven most similar stations on the basis of the meteorological distance score (S), as used for the single station procedure for rainfall. Candidate sets are composed by grouping all combinations of 1, 2, 3 and 4 stations that can be made with these seven stations. This results in 98 sets, and for each set (‘c’) the suitability score is calculated. The importance of a surrounding configuration of a set of stations is accounted for by Δg. This criterion will select a single station (‘a set of one’) for interpolation points nearby that station, a set of two stations for points in a zone in between those stations, three stations for all points situated near the middle in a triangle of stations and four stations for points in the middle of a square of stations. This can be shown by drawing Thiessen polygons around the centres of gravity.

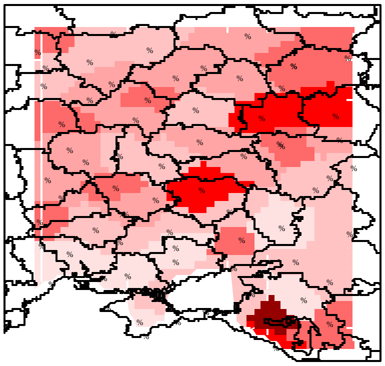
The preference for sets of three or four stations is quantified by adding a penalty to the suitability score of sets containing only one or two stations.

The interpolated value of each meteorological variable is calculated as the average of the values at all the stations in the selected set on the same day, with a correction in temperature and humidity for differences in elevation. This correction is made before averaging. The averaging is carried out without weighing for distance, because in a comparative test it appeared that weighing did not improve the accuracy. This is not surprising, because the procedure for selecting the optimum set of stations contains already a weighing element.

Annex 2 Monthly rainfall sums during growing seasons 1994 - 1997



April 1994



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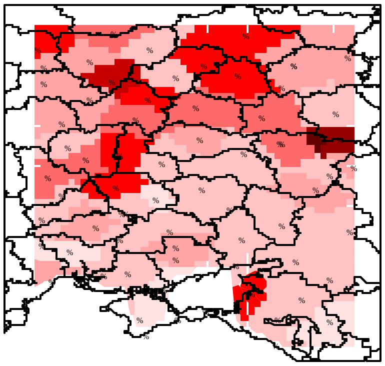

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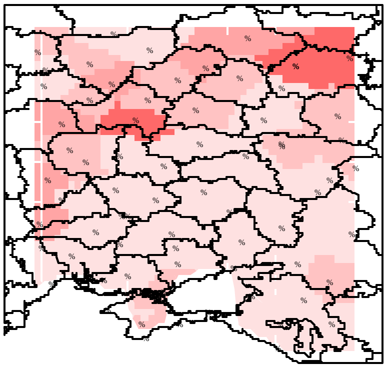

July 1994

Rainfall (mm per month)

- 🟥 0 - 25
- 🟥 25 - 50
- 🟥 50 - 75
- 🟥 75 - 100
- 🟥 100 - 125
- 🟥 125 - 150
- 🟥 150 - 175
- 🟥 175 - 200
- % rainfall stations

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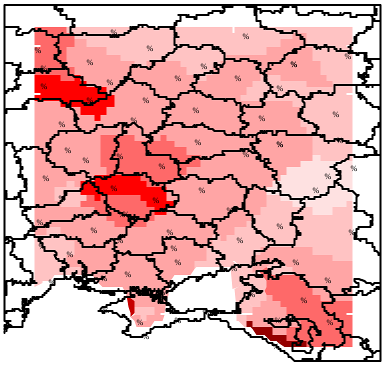

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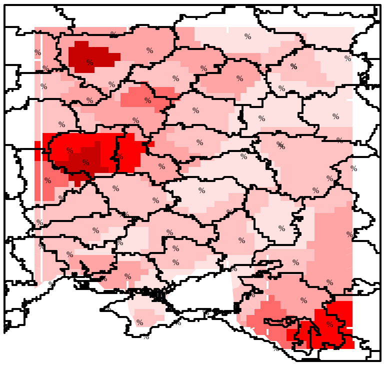

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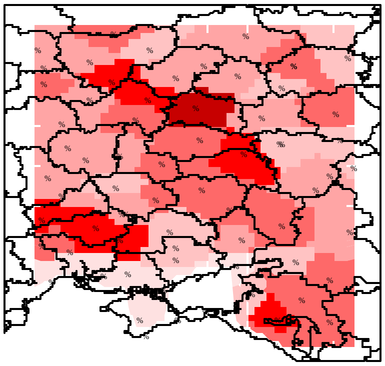
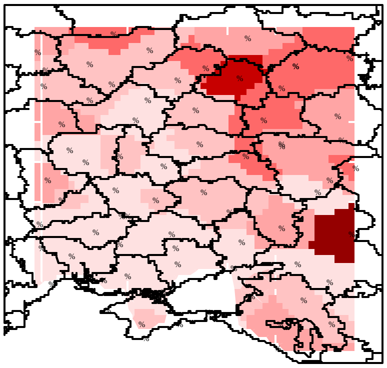


June1995



July 1995

Rainfall (mm per month)

- 🟥 0 - 25
- 🟥 25 - 50
- 🟥 50 - 75
- 🟥 75 - 100
- 🟥 100 - 125
- 🟥 125 - 150
- 🟥 150 - 175
- 🟥 175 - 200
- % rainfall stations

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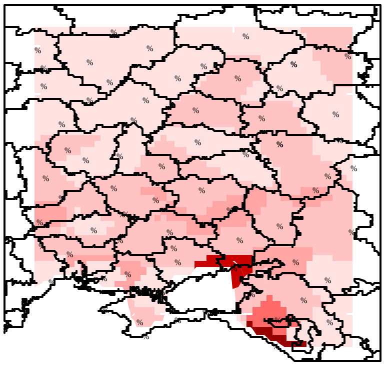

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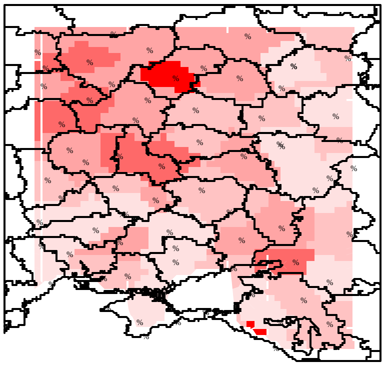

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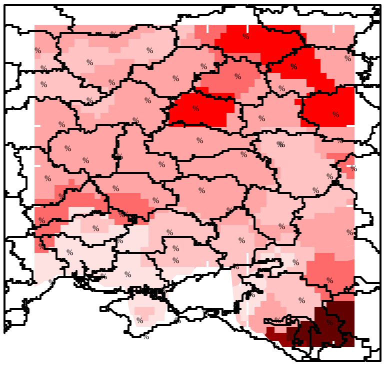
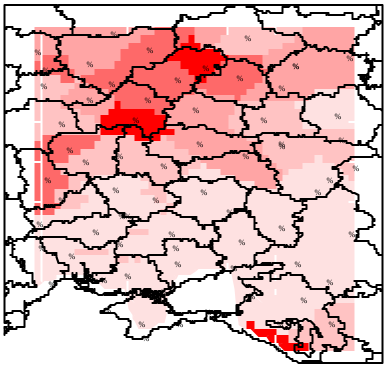


June1996



July 1996

Rainfall (mm per month)

🟥 0 - 25
🟥 25 - 50
🟥 50 - 75
🟥 75 - 100
🟥 100 - 125
🟥 125 - 150
🟥 150 - 175
🟥 175 - 200
% rainfall stations

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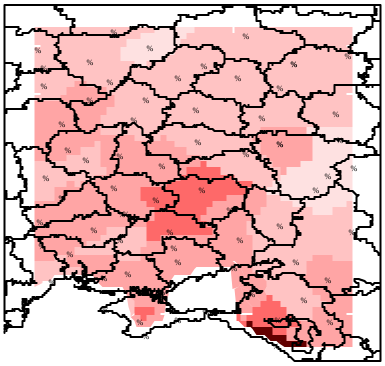
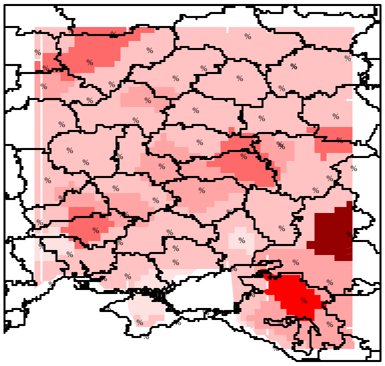
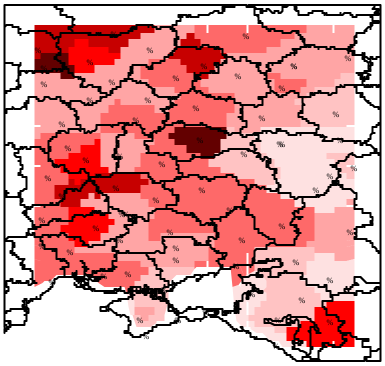


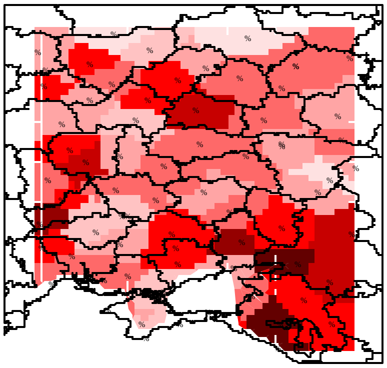
April 1997



May 1997



June1997



July 1997

Rainfall (mm per month)

- ■ 0 - 25
- ■ 25 - 50
- ■ 50 - 75
- ■ 75 - 100
- ■ 100 - 125
- ■ 125 - 150
- ■ 150 - 175
- ■ 175 - 200
- % rainfall stations

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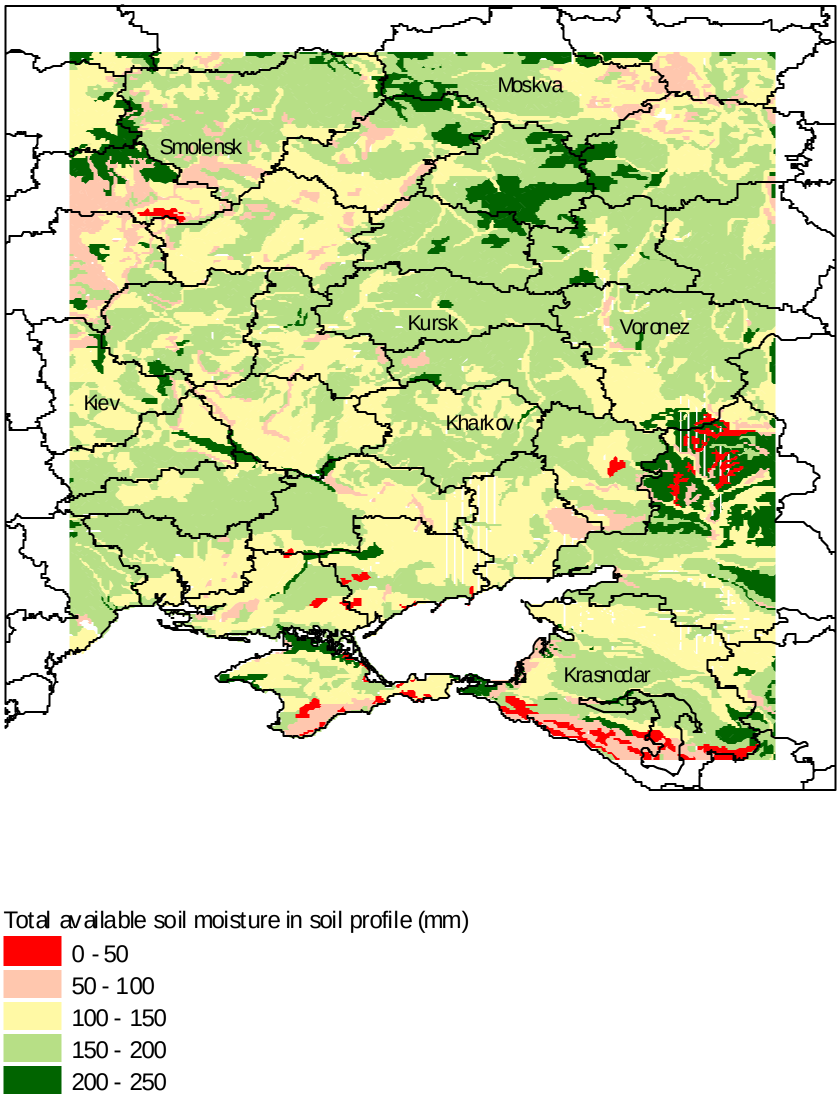
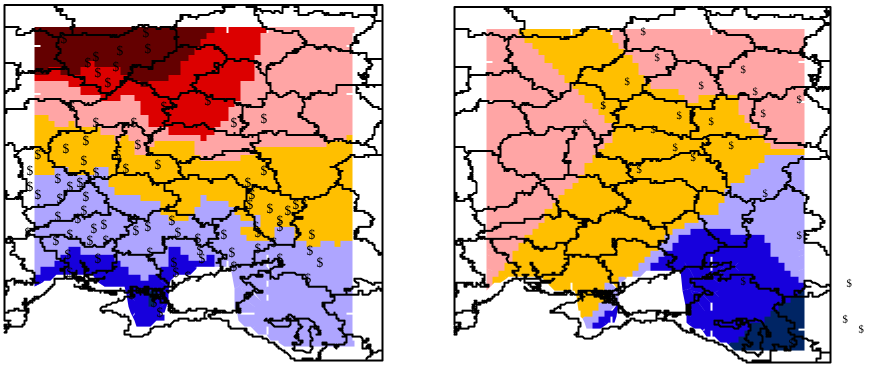
Annex 3 Total available soil moisture in soil profile in Russia and Ukraine

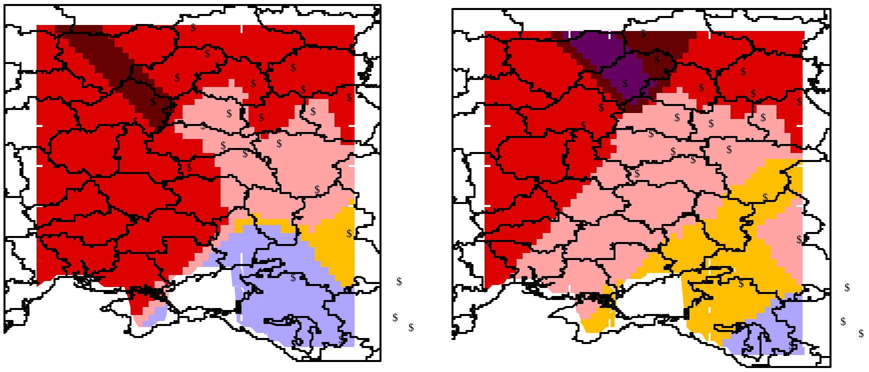


Annex 4 Estimated sowing date for barley in Russia and Ukraine



Long term average

1995



1997

1998

Julian days

■ 70 - 80
■ 80 - 90
■ 90 - 100
■ 100 - 110
■ 110 - 120
■ 120 - 130
■ 130 - 140
■ 140 - 160

$ Vegetation stations used for interpolation

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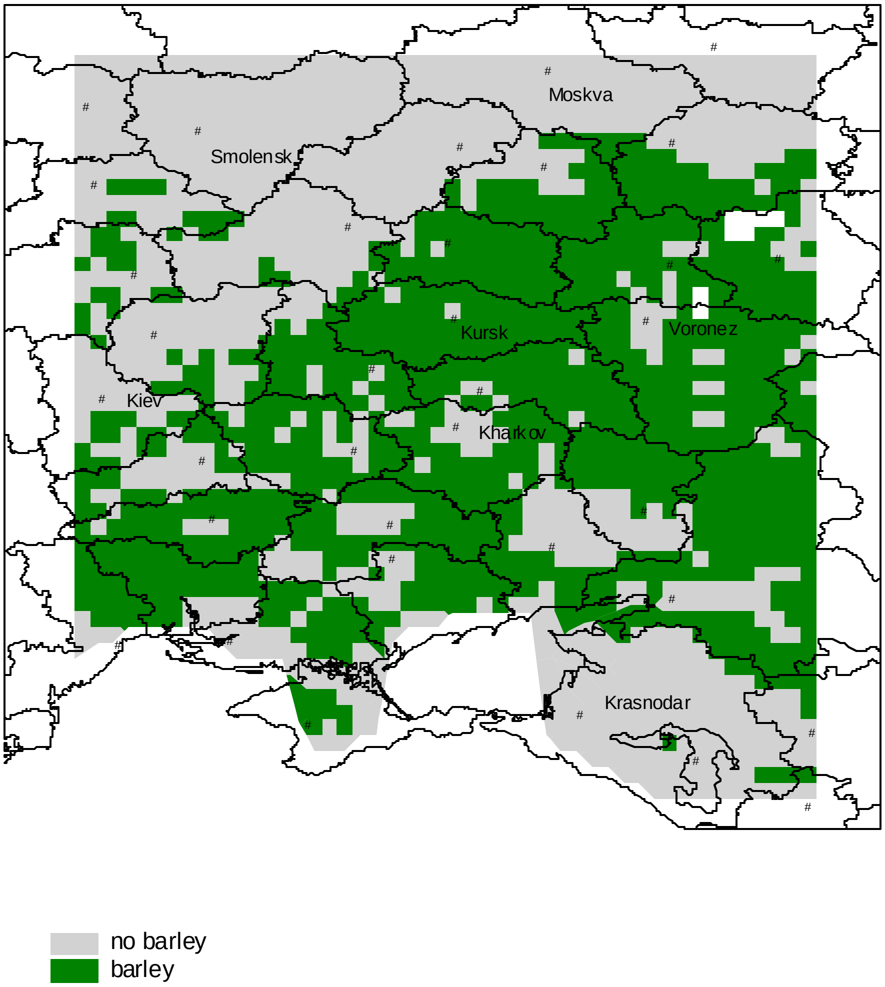
Annex 5 Crop parameters barley

```
** BARLEY, SPRING
** Regions: Whole of the European Communities
** Sowing date varying from 9 Feb in Greece and southern Spain,
** to 26 Mar in southern Germany.
** Mean date of flowering varying from 1 May in the south to
** 19 June in the north.
** Mean date of maturity varying from 20 June in the south to
** 15 Aug in the north.
** Calibrated for use in WOFOST model at the Centre for Agrobiological
** Research (CABO-DLO) for the simulation of crop growth and yield on the
** basis of daily weather data.
** Purpose of application: Crop growth monitoring with agrometeorological
** model in the EC.
** Developed in the framework of JRC Agriculture Project Action 3.


CRPNAM='Spring barley 301, EC'

** emergence
TBASEM   =   0.0    ! lower threshold temp. for emergence [cel]
TEFFMX   =  30.0    ! max. eff. temp. for emergence [cel]
TSUMEM   = 110.     ! temperature sum from sowing to emergence [cel d]

** phenology
IDSL     =   0      ! indicates whether pre-anthesis development depends
                    ! on temp. (=0), daylength (=1) , or both (=2)
DLO      = -99.0    ! optimum daylength for development [hr]
DLC      = -99.0    ! critical daylength (lower threshold) [hr]
TSUM1    = 800.     ! temperature sum from emergence to anthesis [cel d]
TSUM2    = 750.     ! temperature sum from anthesis to maturity [cel d]
DTSMTB   =   0.00,    0.00,     ! daily increase in temp. sum
            35.00,   35.00,     ! as function of av. temp. [cel; cel d]
            45.00,   35.00
DVSEND   =   2.00   ! development stage at harvest (= 2.0 at maturity [-])

** initial
TDWI     =  60.00   ! initial total crop dry weight [kg ha-1]
LAIEM    =   0.274  ! leaf area index at emergence [ha ha-1]
RGRLAI   =   0.0075 ! maximum relative increase in LAI [ha ha-1 d-1]

** green area
SLATB    =   0.00,    0.0020,   ! specific leaf area
             0.30,    0.0035,    ! as a function of DVS [-; ha kg-1]
             0.90,    0.0025,
             1.45,    0.0022,
             2.00,    0.0022
SPA      =   0.000  ! specific pod area [ha kg-1]
SSA      =   0.000  ! specific stem area [ha kg-1]
SPAN     =  25.     ! life span of leaves growing at 35 Celsius [d]
TBASE    =   0.0    ! lower threshold temp. for ageing of leaves [cel]

** assimilation
KDIF   = 0.440      ! extinction coefficient for diffuse visible light [-]
EFF    = 0.40       ! light-use effic. single leaf [kg ha-1 hr-1 j-1 m2 s]
AMAXTB   =   0.00,   35.00,     ! max. leaf CO2 assim. rate
             1.20,   35.00,     ! function of DVS [-; kg ha-1 hr-1]
             2.00,    5.00
TMPFTB   =   0.00,    0.00,     ! reduction factor of AMAX
          10.00,    1.00,     ! as function of av. temp. [cel; -]
            30.00,    1.00,
            35.00,    0.00
TMNFTB   =   0.00,    0.00,     ! red. factor of gross assim. rate
             3.00,    1.00      ! as function of low min. temp. [cel; -]
```

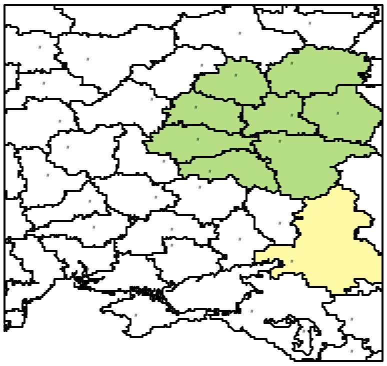
```
** conversion of assimilates into biomass
CVL      =   0.720  ! efficiency of conversion into leaves [kg kg-1]
CVO      =   0.740  ! efficiency of conversion into storage org. [kg kg-1]
CVR      =   0.720  ! efficiency of conversion into roots [kg kg-1]
CVS      =   0.690  ! efficiency of conversion into stems [kg kg-1]

** maintenance respiration
Q10      =   2.0    ! rel. incr. in resp. rate per 10 Cel temp. incr. [-]
RML      =   0.030  ! rel. maint. resp. rate leaves [kg CH2O kg-1 d-1]
RMO      =   0.010  ! rel. maint. resp. rate stor.org. [kg CH2O kg-1 d-1]
RMR      =   0.010  ! rel. maint. resp. rate roots [kg CH2O kg-1 d-1]
RMS      =   0.015  ! rel. maint. resp. rate stems [kg CH2O kg-1 d-1]
RFSETB   =   0.00,    1.00,     ! red. factor for senescence
             2.00,    1.00      ! as function of DVS [-; -]

** partitioning
FRTB     =   0.00,    0.60,     ! fraction of total dry matter to roots
             0.40,    0.55,     ! as a function of DVS [-; kg kg-1]
             1.00,    0.00,
             2.00,    0.00
FLTB     =   0.00,    1.00,     ! fraction of above-gr. DM to leaves
             0.33,    1.00,     ! as a function of DVS [-; kg kg-1]
             0.80,    0.40,
             1.00,    0.10,
             1.01,    0.00,
             2.00,    0.00
FSTB     =   0.00,    0.00,     ! fraction of above-gr. DM to stems
             0.33,    0.00,     ! as a function of DVS [-; kg kg-1]
             0.80,    0.60,
             1.00,    0.90,
             1.01,    0.15,
             2.00,    0.00
FOTB     =   0.00,    0.00,     ! fraction of above-gr. DM to stor. org.
             0.80,    0.00,     ! as a function of DVS [-; kg kg-1]
             1.00,    0.00,
             1.01,    0.85,
             2.00,    1.00

** death rates
PERDL    =   0.030  ! max. rel. death rate of leaves due to water stress
RDRRTB   =   0.00,    0.000,    ! rel. death rate of stems
             1.50,    0.000,    ! as a function of DVS [-; kg kg-1 d-1]
             1.5001,  0.020,
             2.00,    0.020
RDRSTB   =   0.00,    0.000,    ! rel. death rate of roots
             1.50,    0.000,    ! as a function of DVS [-; kg kg-1 d-1]
             1.5001,  0.020,
             2.00,    0.020

** water use
CFET     =   1.00   ! correction factor transpiration rate [-]
DEPNR    =   4.5    ! crop group number for soil water depletion [-]
IAIRDU   =   0      ! air ducts in roots present (=1) or not (=0)

** rooting
RDI      =  10.     ! initial rooting depth [cm]
RRI      =   2.    ! maximum daily increase in rooting depth [cm d-1]
RDMCR    = 125.     ! maximum rooting depth [cm]

** nutrients
** maximum and minimum concentrations of N, P, and K
** in storage organs        in vegetative organs [kg kg-1]
NMINSO   =   0.0110 ;       NMINVE   =   0.0035
NMAXSO   =   0.0350 ;       NMAXVE   =   0.0120
PMINSO   =   0.0016 ;       PMINVE   =   0.0004
PMAXSO   =   0.0060 ;       PMAXVE   =   0.0025
KMINSO   =   0.0030 ;       KMINVE   =   0.0070
KMAXSO   =   0.0080 ;       KMAXVE   =   0.0280
YZERO    = 200.     ! max. amount veg. organs at zero yield [kg ha-1]
NFIX     =   0.00   ! fraction of N-uptake from biol. fixation [kg kg-1]
```

Annex 6 The occurence of barley in Russia and Ukraine

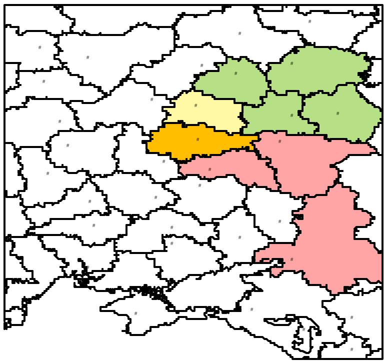


Annex 7 Drought stress of barley in Russia in 1994 (oblast level)

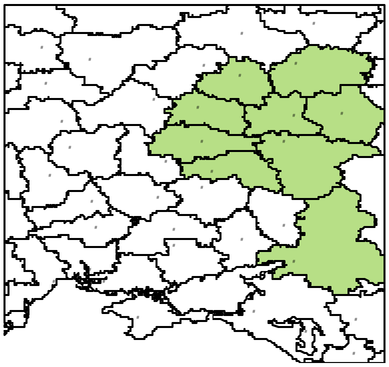
A Calculated with WOFOST using soil moisture data retrieved from ERS scatterometer data



B Calculated with WOFOST using soil moisture data calculated with a water balance model)



C Regional statistics

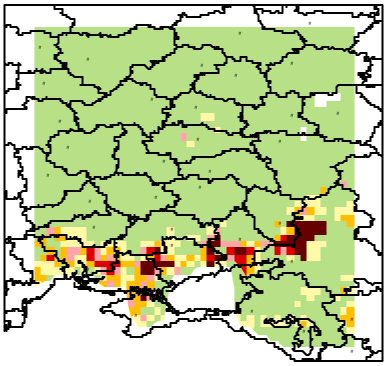


Drought stress
(expressed as percentage reduction of potential grown grain yield)

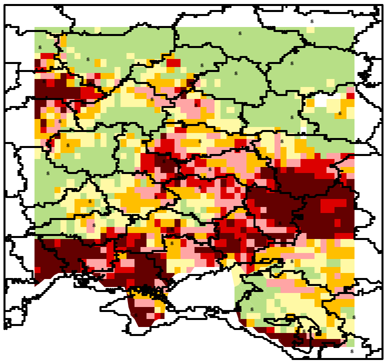
- 🟩 0 - 10
- 🟨 10 - 20
- 🟧 20 - 30
- 🟥 30 - 40
- 🟥 40 - 50
- 🟫 > 50
- ⬜ unknown

Annex 8 Drought stress of barley in Russia in 1994 (grid level)

A Calculated with WOFOST using soil moisture data retrieved from ERS scatterometer data



B Calculated with WOFOST using soil moisture data calculated with a water balance model)

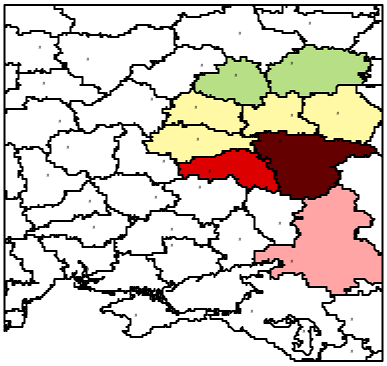


Drought stress
(expressed as percentage reduction of potential grown grain yield)

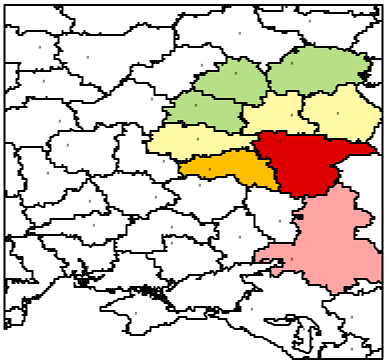
- 🟩 0 - 10
- 🟨 10 - 20
- 🟧 20 - 30
- 🟥 30 - 40
- 🟥 40 - 50
- 🟫 > 50
- ⬜ unknown

Annex 9 Drought stress of barley in Russia in 1995 (oblast level)

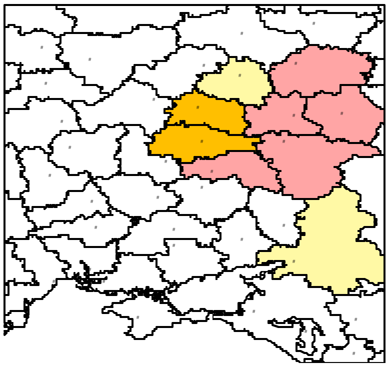
A Calculated with WOFOST using soil moisture data retrieved from ERS scatterometer data



B Calculated with WOFOST using soil moisture data calculated with a water balance model)



C Regional statistics

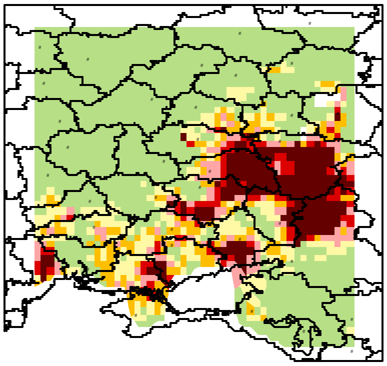


Drought stress
(expressed as percentage reduction of potential grown grain yield)

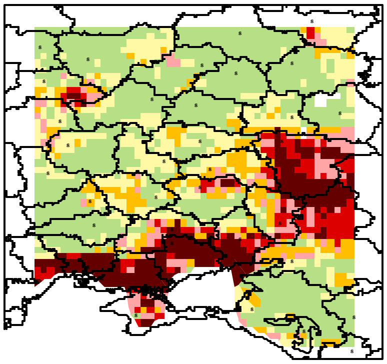
- 🟩 0 - 10
- 🟨 10 - 20
- 🟧 20 - 30
- 🟥 30 - 40
- 🟥 40 - 50
- 🟫 > 50
- ⬜ unknown

Annex 10 Drought stress of barley in Russia in 1995 (grid level)

A Calculated with WOFOST using soil moisture data retrieved from ERS scatterometer data



B Calculated with WOFOST using soil moisture data calculated with a water balance model)

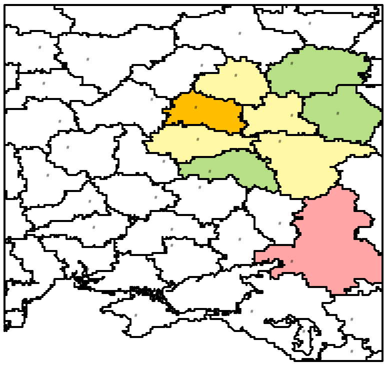


Drought stress
(expressed as percentage
reduction of potential grown
grain yield)

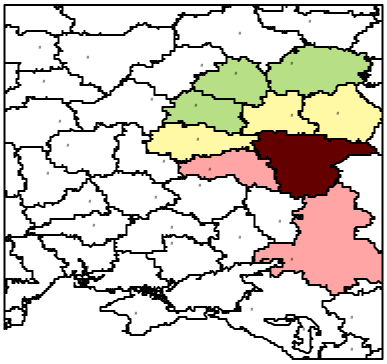
- 🟩 0 - 10
- 🟨 10 - 20
- 🟧 20 - 30
- ▨ 30 - 40
- 🟥 40 - 50
- 🟫 > 50
- ⬜ unknown

Annex 11 Drought stress of barley in Russia in 1996 (oblast level)

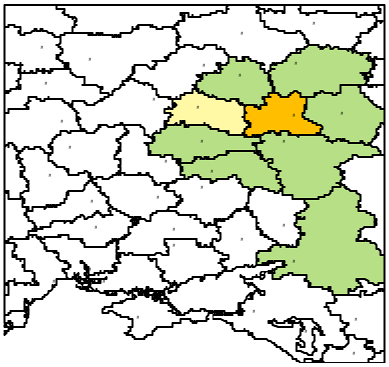
A Calculated with WOFOST using soil moisture data retrieved from ERS scatterometer data



B Calculated with WOFOST using soil moisture data calculated with a water balance model)



C Regional statistics

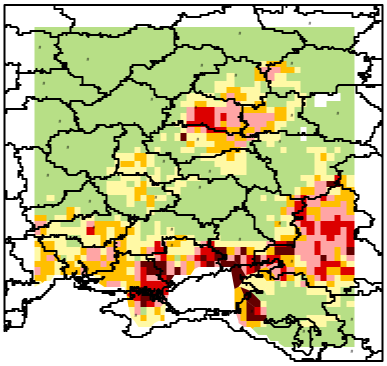


Drought stress (expressed as percentage reduction of potential grown grain yield)

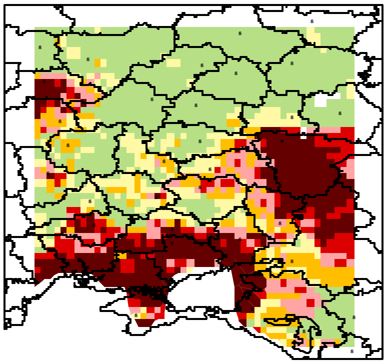
🟩 0 - 10
🟨 10 - 20
🟧 20 - 30
🟥 30 - 40
🟥 40 - 50
🟫 > 50
⬜ unknown

Annex 12 Drought stress of barley in Russia in 1996 (grid level)

A Calculated with WOFOST using soil moisture data retrieved from ERS scatterometer data



B Calculated with WOFOST using soil moisture data calculated with a water balance model)



Drought stress
(expressed as percentage
reduction of potential grown
grain yield)

🟩 0 - 10
🟨 10 - 20
🟧 20 - 30
■ 30 - 40
🟥 40 - 50
🟫 > 50
⬜ unknown

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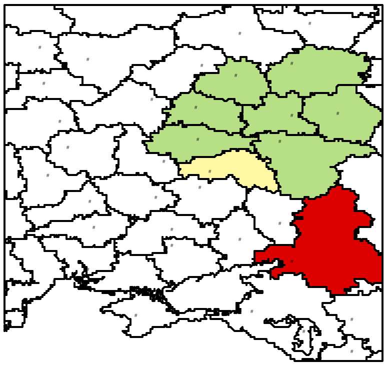
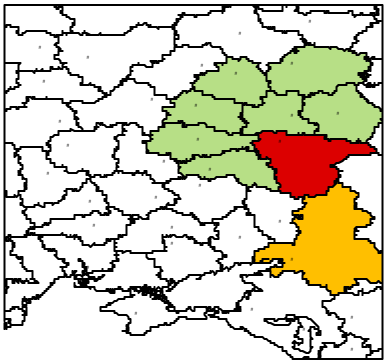
Annex 13 Drought stress of barley in Russia in 1997 (oblast level)

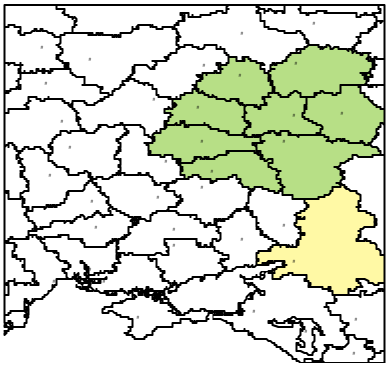
A Calculated with WOFOST using soil moisture data retrieved from ERS scatterometer data



B Calculated with WOFOST using soil moisture data calculated with a water balance model)



C Regional statistics

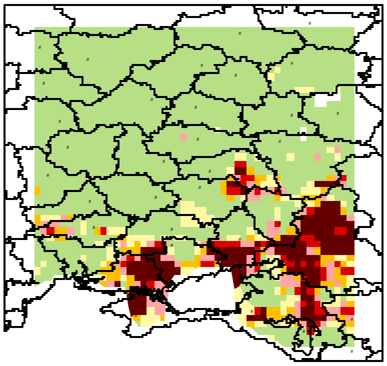


Drought stress
(expressed as percentage reduction of potential grown grain yield)

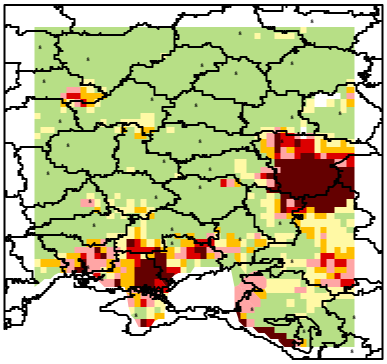
- 🟩 0 - 10
- 🟨 10 - 20
- 🟧 20 - 30
- ▨ 30 - 40
- 🟥 40 - 50
- 🟫 > 50
- ⬜ unknown

Annex 14 Drought stress of barley in Russia in 1997 (grid level)

A Calculated with WOFOST using soil moisture data retrieved from ERS scatterometer data



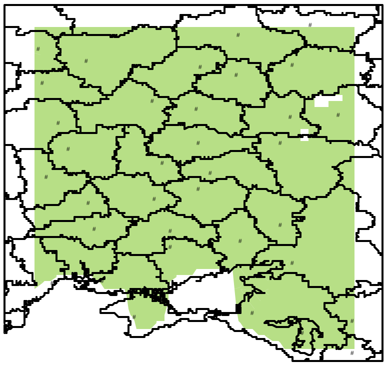
B Calculated with WOFOST using soil moisture data calculated with a water balance model)



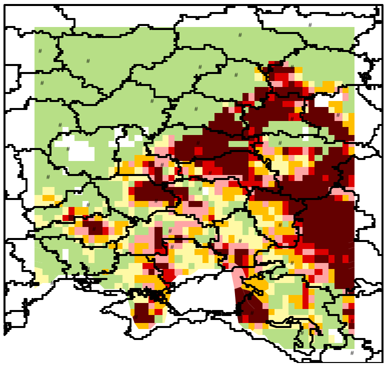
Drought stress
(expressed as percentage reduction of potential grown grain yield)

- 🟩 0 - 10
- 🟨 10 - 20
- 🟧 20 - 30
- 🟥 30 - 40
- 🟥 40 - 50
- 🟫 > 50
- ⬜ unknown

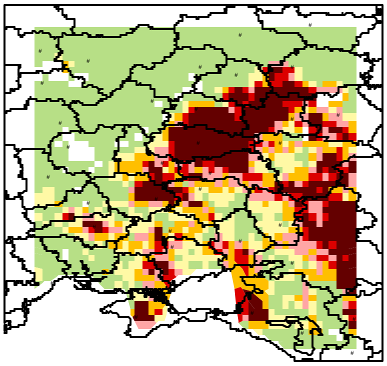
Annex 15 Drought stress of barley in Russia 1999 simulated with scat metho



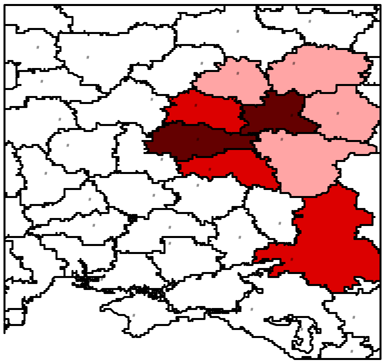
End of May (grid level)



End of June (grid level)



End of July (grid level)



End of growing season (oblast level)

Drought stress
(expressed as percentage
reduction of potential grown
grain yield)

🟩 0 - 10
🟨 10 - 20
🟧 20 - 30
🟪 30 - 40
🟥 40 - 50
🟫 > 50
⬜ unknown

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