Climate Services 34 (2024) 100478

Contents lists available at ScienceDirect

Climate Services

journal homepage: www.elsevier.com/locate/cliser

Grid based monitoring and forecasting system of cropping conditions and risks by agrometeorological indicators in Austria – Agricultural Risk Information System ARIS

Josef Eitzinger [a,b,*], Voiko Daneu [a], Gerhard Kubu [a], Sabina Thaler [a,b], Mirek Trnka [b], Andreas Schaumberger [c], Stefan Schneider [d], Thi Mai Anh Tran [e]

[a] Institute of Meteorology and Climatology, BOKU University, Gregor-Mendel-Straße 33, 1180 Vienna, Austria
[b] Global Change Research Institute CAS, Brno, Czech Republic
[c] Agricultural Research and Education Centre Raumberg-Gumpenstein, Austria
[d] Federal Institute for Geology, Geophysics, Climatology and Meteorology (GeoSphere Austria), Austria
[e] Thai Nguyen University of Agriculture and Forestry (TUAF), Thai Nguyen, Viet Nam

ARTICLE INFO

Keywords:
Agrometeorology
Modelling system
Indicators
Forecasting
Cropping risks
Climate change
Drought
Heat
Frost
Crop stress

ABSTRACT

ARIS (Agricultural Risk Information System) is a GIS (Geographical Information System)-based modelling system (applicable for hind-casting, weather observations and forecasting as well as climate scenario projections) for a number of weather-related abiotic and biotic cropping risks, crop management and growing conditions. In our study we demonstrate and describe the functionality and characteristics of ARIS on Austrian conditions and domain. ARIS indicators can be applied for different time periods on a daily base and a spatial grid of 1 km for weather/climate conditions (0,5 km for soil conditions based on the available Austrian soil map). The currently implemented indicators for general cropping conditions or risks are based on daily weather variables, partly combined with soil wetness, regardless other potential (not weather related) limitations. Crop specific risk indicators are based on algorithms for phenological development of currently 5 main crops and include especially the soil-crop water balance and combined drought and heat stress effects. Biotic indicators include pests and diseases of importance for Austrian conditions. ARIS allows the combined assessment of abiotic and biotic risks during crop growing seasons and thus provides a wide set of information for decision support or strategic planning for stakeholders in the agricultural sector. The system has the potential to be adapted for diverse agroecosystems or be extended by further weather related abiotic or biotic indicators or crop types, if the necessary (grid based) input data formats are available.

Practical Implications

Weather-related cropping risks can vary widely in their nature and seasonal frequency. They include weather phenomena that directly and indirectly affect crop growing conditions and yield and damage potential. Examples are drought and heat impacts (that directly limit assimilation or yield formation process), overwintering conditions of winter crops (especially severe temperature fluctuations and snow cover conditions), frost risks at various phenological stages, risks to seeding and germination (soil erosion risk, inadequate soil wetness and temperatures), adverse weather conditions causing yield loss such as wet periods with strong winds (through lodging, N leaching, erosion), high humidity and leaf wetness (forcing fungal diseases), high temperatures (forcing insect pests) and others. The susceptibility of a crop to the severity and duration of these phenomena varies because a crop's vulnerability to the severity and duration of adverse weather impacts is different by species and variety, phenological status or the combined occurrence of other crop stresses at the same time, which should be considered if suitable for the specific risk.

Reflecting on the gap of available tools of the above-mentioned challenges, we present a GIS-based high spatial and temporal scale modelling system (Agricultural Risk Information System –

* Corresponding author at: University of Natural Resources and Life Sciences Vienna, Gregor-Mendel-Straße 33, 1180 Vienna, Austria.
E-mail address: josef.eitzinger@boku.ac.at (J. Eitzinger).

https://doi.org/10.1016/j.cliser.2024.100478
Received 21 June 2023; Received in revised form 20 April 2024; Accepted 22 April 2024
Available online 5 May 2024

ARIS) containing specific models, algorithms and indicators, applicable on hind-casting, near real-time weather observations, short to medium forecasting as well as long term prediction (climate scenarios) data for the simulation of cropping conditions and risks. The system allows the calculation of crop phenology and biomass development of currently 5 main crops and related crop type specific drought and heat stress level and impacts on biomass development at a simplified level (FAO approach according to Allen et al., 1998) as well as a number of crop-type independent abiotic growing condition indicators and risks. Further selected important pest and disease algorithms, calibrated for Austrian conditions, are implemented as a complementary source for weather related biotic risks.

ARIS is using available gridded high-resolution data sources at 1 km (weather variables) and 500 m (soil layer specific available water capacity) spatial grid base which is demonstrated in this paper for Austria. It must be kept in mind that the spatial resolution does not represent real field sizes at the farm level and thus has limited suitability for many precision farming applications such as irrigation or fertilization scheduling. However, ARIS provides a sophisticated overview on multiple cropping risks and conditions in combination at a high spatial and temporal resolution for different lead times, as a valuable source for identifying spatial development of risks or hot spot regions. ARIS is adaptable for potential other regions, extension for other input data sources (such as remote sensing data) and additional algorithms or indicators, depending on the needs of different stakeholders in the agricultural sector for decision support (e.g. farmers or producers for crop management planning, agricultural extension and warning services, breeding companies and policy institutions for strategic planning).

Technically, ARIS is suitable for application of relevant spatial–temporal indicator based near real-time monitoring as well as for hind- and forecasting for different lead times (1 km grid-based and daily time step) to be processed at an expert level. Interfaces to stakeholders for presentation and visualization of the simulated results are not part of ARIS, but can be designed at various platforms and according to specific tailored stakeholder needs, independently. The operational management of the ARIS-System can be trained and made by one person with basic IT skills, however, modification of algorithms or the design of visualization and information transfer (front end) to stakeholders needs sophisticated GIS Knowledge and Skills or the involvement of relevant IT-services.

In this paper we present the concept and design of ARIS, as well as visualized examples of simulated spatial cropping risks, applied at the Austrian domain.

Introduction

Agriculture is considered one of the sectors most affected by climate change, both globally and in Austria. Especially agricultural crop production is not only very sensitive to changes in mean climate parameters but especially to a shift or change in the occurrence and severity of weather extremes (e.g., Lobell et al., 2009; Trnka et al., 2011; Yue et al., 2019). However, climate and climate variability as well as other environmental conditions, such as soils (Dornik et al., 2024), differ significantly in their characterization by location, as demonstrated by the diverse methods of climate zonation and mapping (Metzger et al., 2005). Climate change is also leading to a shift in agro-climatic zones in Central Europe, with significant consequences for crops production potential and risk (Eitzinger et al., 2013; Elsgaard et al., 2012; Marteau-Bazouni et al., 2024; Olesen et al., 2011; Thaler et al., 2012; Trnka et al., 2013). These changes further pose multiple challenges for the need to develop adaptation options in agriculture (Abramoff et al., 2023), which have to consider additionally other environmental (soil, hydrology, orography) conditions, local agro-ecosystems and agricultural production systems as well as socio-economic conditions (Zhao et al., 2022; Baekelandt et al., 2023). For example, due to the complex orography of the Alpine region, Austria has strong climatic gradients (Gobiet et al., 2014) and associated high spatial variation in soil types as well as differentiation of agricultural production systems (Schönhart et al., 2014). Therefore, complex and severe shifts in weather-related agricultural production conditions can be expected under climate change conditions in Austria (APCC, 2014).

Especially spatial and seasonal changes in climatic conditions affect the frequency and intensity of weather extremes associated with crop damage (Tebaldi et al., 2006), and there is evidence that these weather-related phenomena (or adverse weather conditions) are changing the cropping methods and patterns of specific agricultural crop production regions. For example, Trnka et al. (2014) reported that a multiple increase in the frequency of some agrometeorological extremes is expected across Europe, particularly in relation to drought and heat. Even if weather extremes do not change in absolute severity and frequency, seasonal shifts in their occurrence and their overlap with critical crop phenological phases can significantly alter regional weather-related risks to crop production.

There is already good knowledge of potential shifts in heat extremes and drought across Europe under climate change scenarios and their implications for crop production (Gourdji et al., 2013; Trnka et al., 2014). However, the knowledge and databases are still limited when it comes to regionalized weather-related cropping risk patterns, including all potential weather-related direct (abiotic) and indirect (biotic) risks and their combined impacts on specific crops and cropping systems. Available studies at the national scale with high spatial resolution often cover medium impacts of climate change, but rarely consider changes in extreme weather and climate events (Kirchner et al., 2015). As a result, there is still high uncertainty in the long-term assessment (e.g. of climate change impacts) as well as short to medium-term forecasts (e.g. of cropping conditions and risks) of regionalized specific and combined weather-related risks useable for tailored farm-level applications (IPCC, 2019) for production risk reduction and adaptation.

For example, during a crop growing season, different weather-related cropping risks can occur at different times, at the same time, or overlapping making it difficult to predict crop yields or planning crop management options. To date, efforts were made within the crop modelling community, e.g. in the MACSUR and AgMIP projects (https://www.macsur.eu, https://www.agmip.org), to better address or predict the single or combined effects of crop stresses, where heat and drought are considered the two most important weather-related risks to crop production under current and future climate change in Europe (Bras et al., 2021; Herrera-Lormendez et al., 2023; Řehoř et al., 2024). Within MACSUR for instance, Maiorano et al. (2017) and Webber et al. (2017) found that crop model improvements (such as estimating canopy temperature) could reduce uncertainty of simulated crop yield response to heat stress. Franke et al. (2020) established a global emulator for main yield determining environmental factors for efficient assessment of regional climate change impacts on crops.

However, there is still a large gap in incorporating many other weather-related risks in the models due to the complexity of the processes involved (Rötter et al., 2011), as well as in providing results with high spatial resolution (Rezaei et al., 2015). This is an important aspect for practical applications, where the need to assess site-specific different cropping risks which may occur during a crop growing season in combination or one after each other is crucial. The development of ARIS is considering these challenges by already implemented basic set of relevant algorithms and indicators for multiple, single or combined (drought and heat) crop stresses. These can, however, further be developed, specified, calibrated for different crop types or environmental conditions when new useable (spatial–temporal) data sets on crop responses to relevant stresses are available. The approach of ARIS allows a holistic view on agricultural production risks and related forecasts, to be applicable for stakeholder needs at different spatial–temporal scales

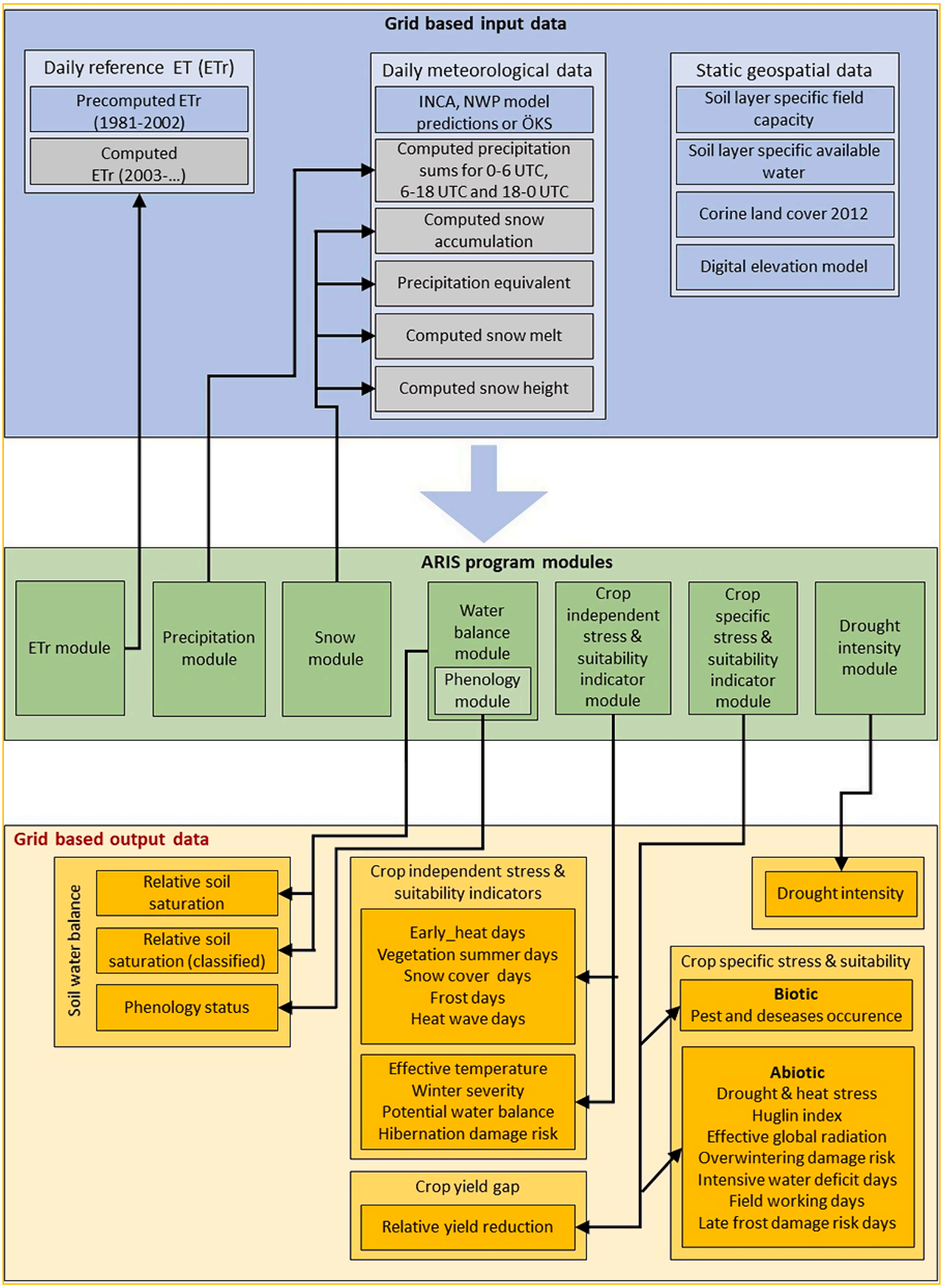

Fig. 1. Overall scheme of ARIS inputs, outputs and processing routines.

(farmers or producers, extension services, breeding companies, environmental agencies and others). We believe that the adaptability of ARIS in view of the large variability and characteristics of agroecosystems over the globe can contribute as a new tool to the global food security challenges posed by climate change and variability.

Conceptual approach of ARIS

The technical goal of the development of ARIS was the creation of an automated system capable of stable and uninterrupted file creation, file handling and file display with minimum human interaction. The development of ARIS includes the integration of parts of previous models such as SpatialGRAM (Schaumberger, 2011) and SOILCLIM (Hlavinka et al., 2011), of new models and algorithms for crop drought stress detection and other weather-related abiotic and biotic crop growth conditions and risk indicators based on spatial weather data input routines. Technically, ARIS was developed using the integrated development environment Eclipse and the object-oriented programming language Java. It is designed to work on a Windows Server with Oracle's Java Runtime Environment (JRE).

The main technical characteristics can be summarized as:

- import of digital meteorological data (up to 3 GB per calculation year depending on the data type of the physical parameter saved in each single netCDF (Network Common Data Form) file), and digital land use, soil and elevation data (12,7 MB) for the Austrian area;
- export of digital result data (e.g. 2,5 TB for the export of the soil water balance computations, of the drought intensity indicator computations and of all selectable crop and suitability indicator computations for a 20-year calculation period);
- computation of soil water balance parameters (soil water content and depletion, evapotranspiration) for all locations (cells) of the study area assigned to specific crops;
- assessment of drought and heat stress-related parameters based on the soil-crop water balance;
- computation of potential crop yield reduction and a number of different cropping conditions and risk indicators (Table 4a,b);
- execution of all computational operations for meteorological hindcasting, near real-term weather observations and forecasts/projections of different origins (INCA, NWP and ÖKS15 as described further below);
- execution of all necessary computation tasks within a reasonable time frame in a fast and efficient way, carefully utilising available computer resources (e.g. one-time import of the entire content of an input file for the calculation of the entire federal territory of Austria or only partial import of the input data for a reduced region of interest; sequential processing of the calculations, cell by cell, with all input data available in the working memory; export of results using different Java data types (primitive data types like "short", "integer" and "float") for different parameters to reduce the required disk space);
- selection of individual indicators to reduce the calculation time;
- selection of three different predefined soil depth combinations (top layer 0–10 cm and sub layer 10–40 cm, top layer 0–20 cm and sub layer 20–40 cm or top layer 0–40 cm and sub layer 40–100 cm);
- export of computation results for selected parameters using the ASCII text file and the netCDF file formats;
- recommended system requirements are:
  - Operating System: Windows® 10 or higher
  - Processor: 3.1 GHz Dual Core CPU or better
  - Memory: 12 GB RAM
  - Hard Disk Space: several TB free (depending on the calculation time period)
  - DVD-ROM Drive & Sound: not required
  - Video: no special requirements

The first major characteristic of ARIS is the coding of adequate I/O interfaces which allow high-performance data access and export. Based on the excellent performance and the relatively small size of netCDF data files, the netCDF file format was chosen as the main format for the creation, access, and sharing of the data. All program features have been implemented as static or instantiable classes in accordance with the object-oriented programming paradigm. All classes with their class methods and the number and types of class variables and, finally, the program structure itself have been optimized with regard to a balanced ratio of standard personal computer memory consumption and processing speed. Furthermore, different methods have been implemented to export intermediate and final results of crucial calculation steps (Fig. 1) in ASCII text file format for evaluation and graphical visualisation purposes.

ARIS is designed as a modular system controlled by two main control modules (Fig. 1). One control module runs the crop independent calculations which solely rely on meteorological input data, while the other control module runs crop dependent calculations based on meteorological AND crop/soil specific information. The user can adjust a limited number of parameters through the graphical user interface GUI which are stored in ASCII text files and included at program start. The computations are performed on a daily basis generating a large number of netCDF export files requiring a few Terabytes of disk space. Conceptually ARIS is designed to keep the number of I/O operations as low as possible to improve overall performance.

The input information is supplied via binary files in netCDF file format. The initial soil and meteorological input files cover the complete territory of Austria using a grid resolution of 500 m (e.g. soil data) or 1000 m (e.g. weather data). The ARIS input classes implement a method that converts the spatial resolution of 1000 m to the final resolution of 500 m.

Secondary meteorological input files (e.g. snow or meltwater) are generated in a first step and stored as netCDF files to avoid multiple calculations in the further course of the program. Essential calculation steps and results of the program are documented for control points specified by the user and exported as a text file. In addition to evaluating the results, this function enables the correct calculation processes to be checked.

ARIS also generates several log files with further information that may be relevant for the subsequent analysis of results (for example, information about implausible or missing values in the meteorological input files).

ARIS offers the option of calculating the selected indicators for a specified area (either the whole Austrian territory or a selected part of it) as well as only for selected grid points in order to save calculation time. The results of the areal calculation are stored as netCDF files and can be visualized and analyzed in a GIS. For punctual calculations, the user can enter a list of locations with names and geographical coordinates. The results of the punctual calculations are exported as a text file in the same way and format as the control point evaluation.

Meteorological input data

Initial weather input data for ARIS are daily based weather parameters as follows:

- Wind speed at 10 m [m s^{-1}]
- Mean air temperature at 2 m for 18–6 UTC and 6–18 UTC [°C]
- Minimum, mean and maximum air temperature at 2 m [°C]
- Mean relative humidity at 2 m [%]
- Global radiation [MJ m^{-2} day^{-1}]
- Precipitation sum for 18–6 UTC, for 6–18 UTC and for 0–24 UTC [mm]

For weather input data in ARIS of past periods, current conditions and short-term forecasting the gridded INCA (Integrated Nowcasting through Comprehensive Analysis, Haiden et al., 2011) product of the Austrian weather service (GeoSphere Austria) is used. Further, numerical weather prediction (NWP) for mid-term to seasonal (3 days up to 6 months) forecast, as well as the for Austrian domain downscaled climate scenarios (ÖKS15) (Chimani et al., 2020) can be applied using the INCA grid input format.

The analysis and nowcasting system INCA algorithmically combines station observations, NWP model output and remote sensing data (radar, satellite) to provide meteorological analysis and nowcasting fields at high temporal (5 min – 1 h, depending on parameter) and spatial (1 km) resolution. INCA is used to calculate analyses and forecasts of a variety

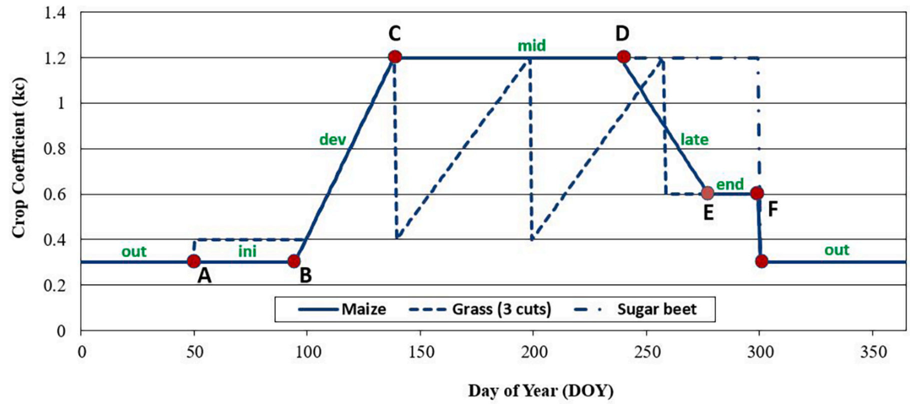

Fig. 2. Kc courses of different ARIS crop types. The blue continuous line represents the Kc courses of grain maize, the blue dashed lines the Kc courses of grass (3 cut regime) and sugar beet. The 2 and 4 cut regimes of grass have Kc courses in accordance with the number of cuts. The graph focuses on the illustration of the phenological stages – the values of the crop coefficients are arbitrary. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of parameters. The INCA analysis and nowcasting system is being developed primarily as a means of providing improved numerical forecast products in the nowcasting range (up to +4 h) and very short range (up to about +12 h) even though it adds value to NWP forecasts up to +48 h through the effects of downscaling and bias correction. INCA products were successfully evaluated, which results were published in Kann et al. (2015) and Ghaemi et al. (2021).

Soil and land use characteristics

The digital elevation model (DEM) of the region of interest with a spatial resolution of 1000 m is applied. The computation of soil water balance furthermore requires the knowledge of the water storage capacity of the soil. For this purpose, the Federal Agency for Water Management (BAW) has derived field capacity and available field capacity information (Murer, 2009; Murer et al., 2004) from the digital soil map "ebod" (BFW, 2023) of the Federal Research and Training Centre for Forests, Natural Hazards and Landscape (BFW). The water storage capacity information has been derived with a resolution of 500 m and for two different soil layers – an upper layer with a thickness of 40 cm and a lower layer with a thickness of 60 cm.

The land use distribution of CLC2012 Corine Land Cover data (EEA, 2023) is so far used for delineation of main growing areas. Corine is a pan-European land cover/land use map and one of its databases is an inventory of land cover in 44 classes. However, the 44 Corine land use classes have been aggregated to 13 for simplification purposes. Partially, specific algorithms can be related to specific land-use types (e.g. grapevine pest algorithms carried out only for vineyard regions).

Land cover information of the region of interest is needed to identify those areas, which are potentially cultivated with specific plants considered by ARIS. Modeling and forecasting of drought and heat stress parameters are carried out only for those land-use types (i.e. arable and grassland) or for the crops related to the arable land use type. The following crops/land use types have been initially selected for the ARIS system: grassland, vineyards, fruit trees & berry plantations and arable land. Arable crops currently include winter wheat, spring barley, maize and sugar beet with the option for extensions, based on calibrated crop development algorithms.

Basic processing steps and outputs

Soil-crop water balance model

ARIS includes the main parts of the SoilClim model (Hlavinka et al., 2011) which simulates soil moisture and soil climate on a daily time step. The approach is based on a modification of the concept and model formulation in FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998), including the Penman-Monteith approach for reference evapotranspiration estimate. The processing steps for crop soil water balance provide the following main output parameters on a daily basis:

- Grass reference evapotranspiration (ETr) [mm]
- Single crop coefficient (Kc Factor) for evapotranspiration, crop interception [mm], crop evapotranspiration without drought stress (ETC) [mm] and actual evapotranspiration (ETA) [mm]
- Soil water content (SWC) for two soil layers [mm]
- Relative soil saturation (RSS) [%] of crop available water for each soil layer (expressed in absolute values as well as in classified values)

ARIS does not calculate surface runoff (except as an input loss factor) or any horizontal water flows from one grid to another as applied in many hydrological models by e.g. "hydrological units". This can be, especially, in case of heavy precipitation, lead to considerable local biases in simulated soil water content, depending on the orography. The soil profile in ARIS can be divided into two layers of 0–40 cm and 40–100 cm or optional into 0–10 cm and 10–40 cm depth or 0–20 cm and 20–40 cm for the soil water balance calculations, allowing better adoption to potential rooting depths of crops. As there is no root growth model incorporated in ARIS, the crop water consumption (soil water uptake) by evapotranspiration of the topsoil layer is weighted with 60 % and the subsoil with 40 % of the total crop evapotranspiration for the considered crops as an approximation (which relationship can by modified depending on crop type). This approach was validated against in-situ soil water content measurements with satisfying results for several sites in Czechia (Trnka et al., 2020) and for Austrian arable crop field site in flat terrain and compared with different alternative methods (Marin, 2021; Thaler et al., Unpublished). The weighting concept implies, that the upper layer provides the major part of available soil water to crop evapotranspiration as long as not depleted, according the general vertical root distribution of major crops applied also in many crop models as approximation. For soil water balance between soil layers the "bucket" approach is used to estimate soil water content and crop available soil water, which does not consider capillary rise. Soil drainage, however, is calculated as a surplus factor from the bucket approach.

ARIS also allows further snow cover estimation from precipitation and air temperature based on the snow model of Trnka et al. (2010). Compared to other crop models, ARIS does not account for any lasting effect of drought stress on the canopy development.

Table 1
Phenological stage entry events of grassland for different cut regimes, calibrated for Austrian conditions (Tbase = 0°C), (Schaumberger, 2011).

	Ini Date (DDMM)	Dev1 Indicator	Dev2 Tsum	Dev3 Tsum	Dev4 Tsum	End Tsum	Out Date (DDMM)
2 cut regime	01.03	SGS	1170 °C			1900 °C	31.10
3 cut regime	01.03	SGS	770 °C	1020 °C		1260 °C	31.10
4 cut regime	01.03	SGS	630 °C	710 °C	910 °C	850 °C	31.10

Table 2
Phenological stage entry events of the four arable land crop types, calibrated for Austrian conditions (Tbase of maize is 8 °C, for all other crops 5 °C).

	Ini Date DDMM	Dev Indicator/ Tsum	Mid Tsum	LateTsum	End days	Out Date DDMM
Winter wheat	01.03	SGS	350 °C	692 °C	+14	30.11
Spring barley	01.03	SGS	502 °C	568 °C	+14	30.11
Maize	01.04	SGS-M	249 °C	1238	+14	30.11
Sugar beet	01.03	300 °C	2400 °C			31.12

Table 3
Phenological stage entry events of apple and grapes, calibrated for Austrian conditions.

	Ini Date DDMM/ Tsum (hourly)	Dev Days/Tsum (hourly)	Mid days	Late days	End days	Out Date DDMM/ days
Grapes	01.04.	+30	+60	+40	+80	30.11
Apple	1000 °C	6250 °C	+70	+90	+30	+14

Crop phenology model

The crop development is defined in terms of phenological development stages with varying Kc factors as a function of calibrated temperature sum (i.e., cumulative daily mean temperature) as well as fixed dates and fixed time periods for Austrian climatic conditions. The respective temperature sums were derived from the results of crop model runs for a 30-year period based on validated representative Austrian crop cultivars under current climate conditions (Thaler et al., 2012).

The effects of canopy development on crop water use that distinguish field crops are integrated into the Kc factor calculations. In compliance with the FAO approach (Allen et al., 1998), 6 phenological stages are implemented in the program's description of the crop coefficients of the so far implemented crops (maize, winter wheat, spring barley, sugar beet, apple and grapes), beside permanent grassland:

1. Stage out (interim): stage with no plant growth during the winter season or bare soil
2. Stage ini: a stage that starts with the sowing event (spring crops) or growing period (winter crops, grassland) and lasts till plant emergence
3. Stage dev: plant development stage till achievement of maximum plant size and canopy cover with linear Kc value increase (represents the vegetative growth period)
4. Stage mid: stage till achievement of plant maturity (vegetative or generative phase of crop growth, depending on the harvested plant part)
5. Stage late: stage between plant physiological maturity and harvest with linear Kc value decrease (drying period to reach harvestable condition)
6. Stage end: stage of soil cultivation (soil tillage) after harvest (bare soil condition)

Table 4a
Crop independent stress and suitability indicators currently implemented in ARIS. Citations with Asterix (*) include calibration and/or validation results of crop or impact responses from at least one site in Austria.

Crop independent stress and suitability indicators	Description	Output format
Snow cover (Trnka et al., 2010)	Number of days with snow cover (snow height at least 30 mm) from September 1st to August 31st.	Cumulative (days)
Early heat stress days	Number of days between January 1st and June 15th with maximum daily temperatures above 28 °C.	Cumulative (days)
Heat wave days	Total number of days per year within episodes when maximum daily temperatures are continuously above 30 °C and the minimum daily temperatures are continuously above 20 °C for at least 3 consecutive days.	Cumulative (days)
Frost stress days	Number of days from September 1st to June 30th with minimum daily temperatures below −10 °C and no continuous snow cover (i.e. snow height below 30 mm).	Cumulative (days)
Winter severity	Sum of freezing temperatures (mean daily temperatures below 0 °C) from September 1st to April 30th	Cumulative (°C)
Sum of effective growing temperatures (Trnka et al., 2011)	Sum of effective temperatures per year for days with minimum daily temperatures equal or above 0 °C, with mean daily temperatures above 10 °C and with maximum daily temperatures equal or below 35 °C.	Cumulative (°C)
Duration of the vegetation summer (Trnka et al., 2011)	Number of days per year with mean daily temperatures continuously above 15 °C (i.e. mean daily temperatures do not drop below this threshold for more than 3 days) and minimum daily temperatures above 0 °C.	Cumulative (days)
Potential water balance	Sum of the differences between the daily precipitation and the daily grass reference evapotranspiration (Allen et al., 1998) from April 1st to June 30th (optionally from April 1st to September 30th).	Cumulative (mm)
General overwintering (hibernation) damage risk probability (winter crops); (Koppensteiner et al., unpublished)*	Combination of crop independent indicators (number of frost stress days, number of days with snow cover), of winter severity (sum of mean daily temperatures below 0 °C), of empirical risk indicators for total snow cover duration and "risk of snow mould" indicator (sum of days with continuous snow coverage ≥ 28 days) from September 1st to April 30th for winter cereals.	Cumulative (probability)

Table 4b
Crop specific stress and suitability indicators currently implemented in ARIS. Citations with Asterix (*) include calibration and/or validation results of crop or impact responses from a least one site in Austria.

Crop specific stress and suitability indicators	Description	Output format
Relative soil saturation (RSS) (Marin, 2021; Thaler et al., Unpublished)*	Crop available soil water depletion over variable reference soil depths, split into two soil layers (top soil and sub soil). Grassland (meadow): 0–10 cm (top) and 10–40 cm (sub) or 0–20 cm (top) and 20–40 cm (sub). Arable crops, apple and grapes: 0–10 cm (top) and 10–40 cm (sub), 0–20 cm (top) and 20–40 cm (sub) or 0–40 cm (top) and 40–100 cm (sub).	Daily (relative)
Drought intensity	Deviation of the actual RSS from the daily long-term mean (1986–2015 period) and the consecutive years (excluding the actual year).	Daily (percentile)
Days with intensive water deficit (Trnka et al., 2011)	Number of days from April 1st to June 30th (optionally from April 1st to September 30th) with crop specific quotients of the actual evapotranspiration and the reference evapotranspiration below 0,4 (ETA/ETr < 0,4).	Cumulative (days)
Combined drought and heat stress indicator (Eitzinger et al., 2016)	Crop related stress indicator for grassland, winter wheat, spring barley, sugar beet and maize, based on RSS and temperature limits.	Daily and cumulative (index)
Yield reduction factor (Eitzinger et al., 2016)*	Potential crop specific yield depression from optimum yield due to combined drought and heat stress indicator (see above). Calculated from start of crop specific growing period till maturity/harvest dates for grassland, winter wheat, spring barley, sugar beet and maize. Empirically calibrated against multi-year farm crop yield reports of north-east Austrian main arable regions (linear regression).	Cumulative (%)
Effective global radiation sum (Trnka et al., 2011)	Sum of daily global radiation values per year during days with mean daily temperatures above 5 °C and crop specific water stress coefficient above 0,4 (ETA/ETr > 0,4).	Cumulative (MJ/m^2)
Field working days (days with soil conditions suitable for drive) (Trnka et al., 2011)	Number of days per month when the mean daily precipitation value on day N is less than 0.5 mm; on day N-1 is less than 5 mm, on day N-2 is less than 10 mm and on day N-3 is less than 20 mm. Moreover, the crop specific soil water content of the soil's upper 20 cm must not be higher than 70 % of the maximum soil water holding capacity.	Cumulative (days)
HUGLIN index for grapes (Huglin, 1978)	The HUGLIN index is a bioclimatic heat index based on the mean and maximum daily temperatures. Temperatures are summed up from April 1st till September 30th.	Cumulative (index)
Apple phenology and late frost risk for apple (Firanj Sremac et al., 2021)*	Considering chilling requirement and temperature sums for flowering time estimate and coincidence with frost occurrence. Three index classes [0 – 3] represent conditions favourable for frost risk (0: outside the flowering period; 1: inside the flowering period, but no frost (t_{min} > 0 °C); 2: inside the flowering period, with late frost risk in exposed or unfavourable locations (t_{min} > -1°C and <= 0 °C); 3: inside the flowering period, with significant late frost risk (t_{min} <= −1°C). Cumulative calculation within the estimated apple flowering period.	Daily (index) and cumulative (days)
Crop specific overwintering (hibernation) damage risk probability (Koppensteiner et al., unpublished)*	Combination of the general hibernation damage risk indicator (see table 14a), of crop specific hibernation damage risk without snow coverage (sum of days with t_{min} < -8°C for winter rape or t_{min} < -14 °C for winter barley) and of winter hardiness risk without snow coverage (sum of days with tmin < -15 °C for winter rape and winter barley) from September 1st to April 30th.	Cumulative (probability)
Peronospora (Plasmopora viticola) incubation period for grapes (Mihailovic et al., 2001)	Estimate of start of infection and incubation period of grapevine downy mildew from April 1st till September 30th. Prerequisites: presence of oospores, shoot length in the vineyard is at least 10 cm, the average temperature is above 10 °C and there was more than 10 mm of rain during the last 48 h. Calibrated so far for conditions in Serbia.	Cumulative (days) and date (DOY)
European grapevine moth occurrence (Blümel et al., 2020)*	First day of occurrence of European grapevine moth (Lobesia botrana) and the European grape berry moth (Eupoecelia ambiguella). Empirical model based on mean daily temperatures, days < 11 °C, days with precipitation and precipitation sum from January till May.	Date (DOY)
Plum fruit moth occurrence (unpublished) *	First day of occurrence of Plum fruit moth (Grapholita funebrana). The temperature sum (Tmean > 11 °C), the global radiation sum and the maximum temperature from February to April are considered.	Date (DOY)
Grapevine cicada occurrence (unpublished) *	Occurrence of nymphal stages 1 and 3 of grapevine cicada (Scaphoideus titanus) are calculated based on global radiation, temperature sums and maximum temperature from February to May (multiple linear regression).	Date (DOY)

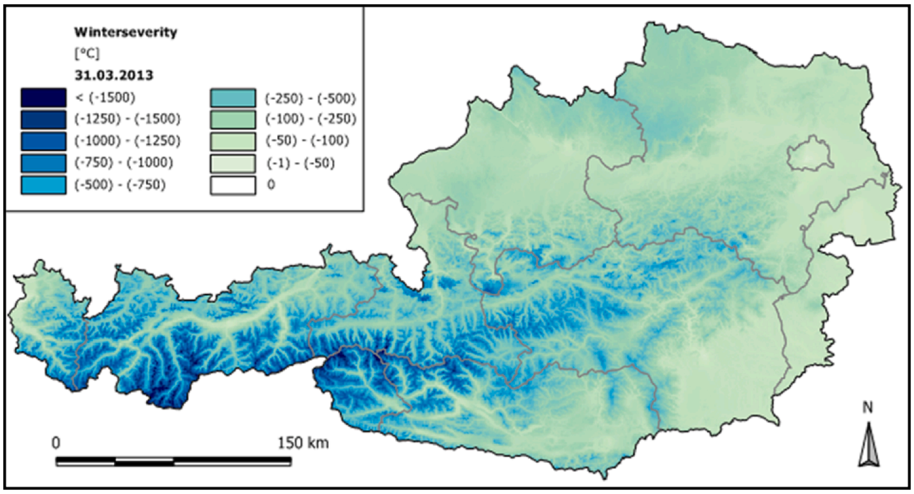

Fig. 3. Winter severity (Table 4a) during winter 2012/2013. Sum of freezing temperatures from November 1st to March 31st. Computation of the indicator for all cells of the model area at a spatial resolution of 1000 m for the whole Austrian terrain.

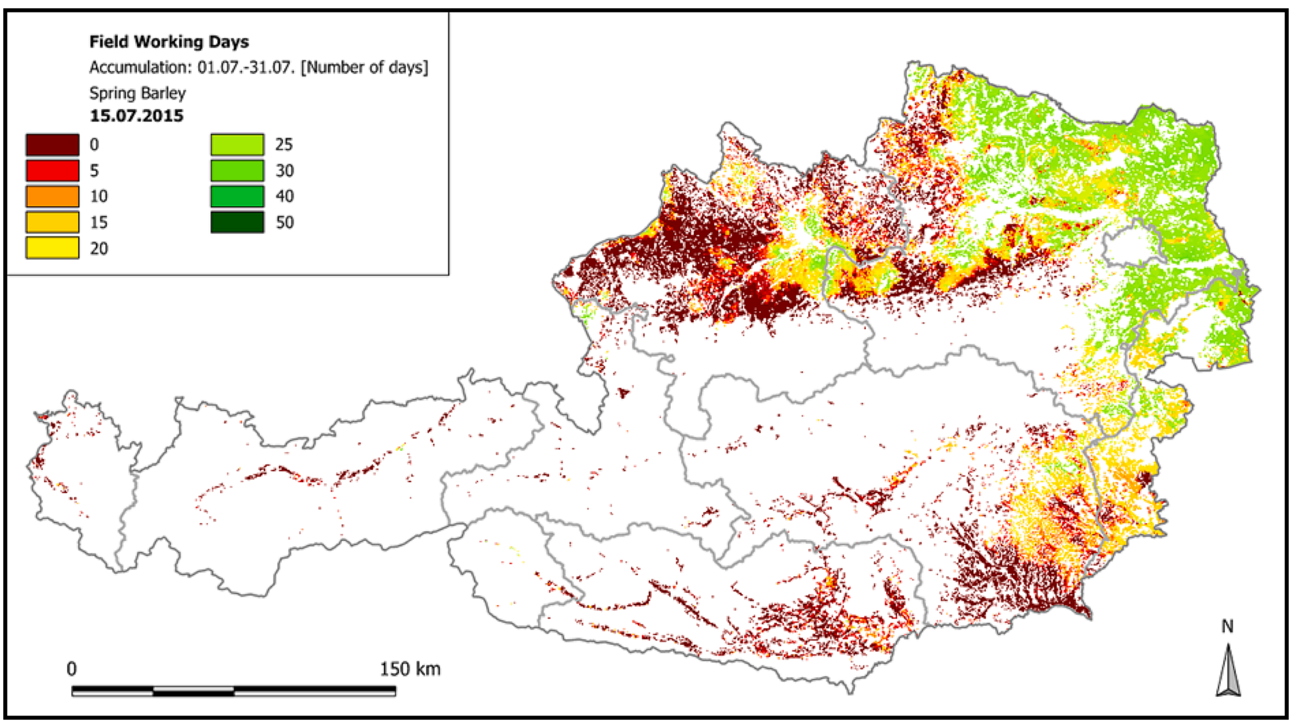

Fig. 4. Field working days (Table 4b) for soils/cells of the CLC 2012 land use type "arable land" (CEC, 1995). Simulation for spring barley at a spatial resolution of 500 m.

Since sugar beet (only vegetative growth till harvest) cannot be forced into the predefined scheme of six phenological stages, a simplified model with 4 stages (out, ini, dev and mid) is used to match the Kc curve as closely as possible to realistic conditions. Due to the multiple harvest feature of cultivated grassland, an adapted crop coefficient scheme is applied in compliance with the corresponding cut regime. In this case, too, fewer different stages are needed to describe the Kc course namely out, ini, dev1-3 and end. Due to multiple harvests of grass, the mid stage is replaced by multiple dev stages, representing only vegetative growth. All these considerations are schematically illustrated in Fig. 2.

The phenological stage entry events for all individual crop types as implemented in ARIS are outlined in Tables 1, 2 and 3. The entry events of the ini and out stages are defined with calendar dates (with exception of apple, which is defined by hourly temperature sum and winter period chilling units). The entry events of the first development stage "Dev1" (crops vegetative growing periods) is defined by the calculated indicator "start of the growing season (SGS)" for grassland, winter wheat, spring barley and maize. The entry events of grassland cutting dates (Dev2, Dev3, Dev4) and crops "Mid" and "Late" season depend on daily mean temperature sums (Tsum) above a crop specific base temperature (Tbase). "Out" is defined for all crops by date or number of days to be added.

ARIS indicators for crop growth conditions and cropping risks

Based on the daily gridded input weather data, ARIS is calculating several agrometeorological indicators, which were found to be relevant for Austrian agro-ecosystem conditions. Part of these indicators use

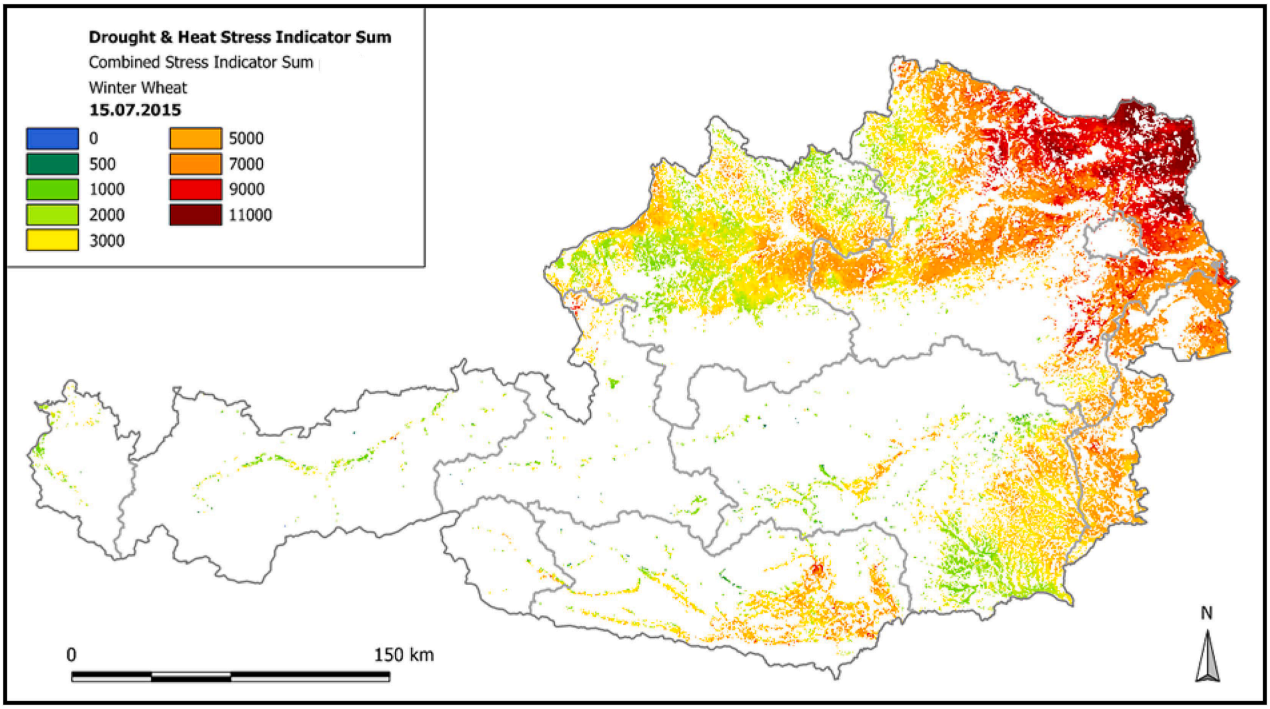

Fig. 5. Combined drought and heat stress indicator (Table 4b) for winter wheat growing season, cumulative till specific date (15th July 2015, which is approximate harvest time).

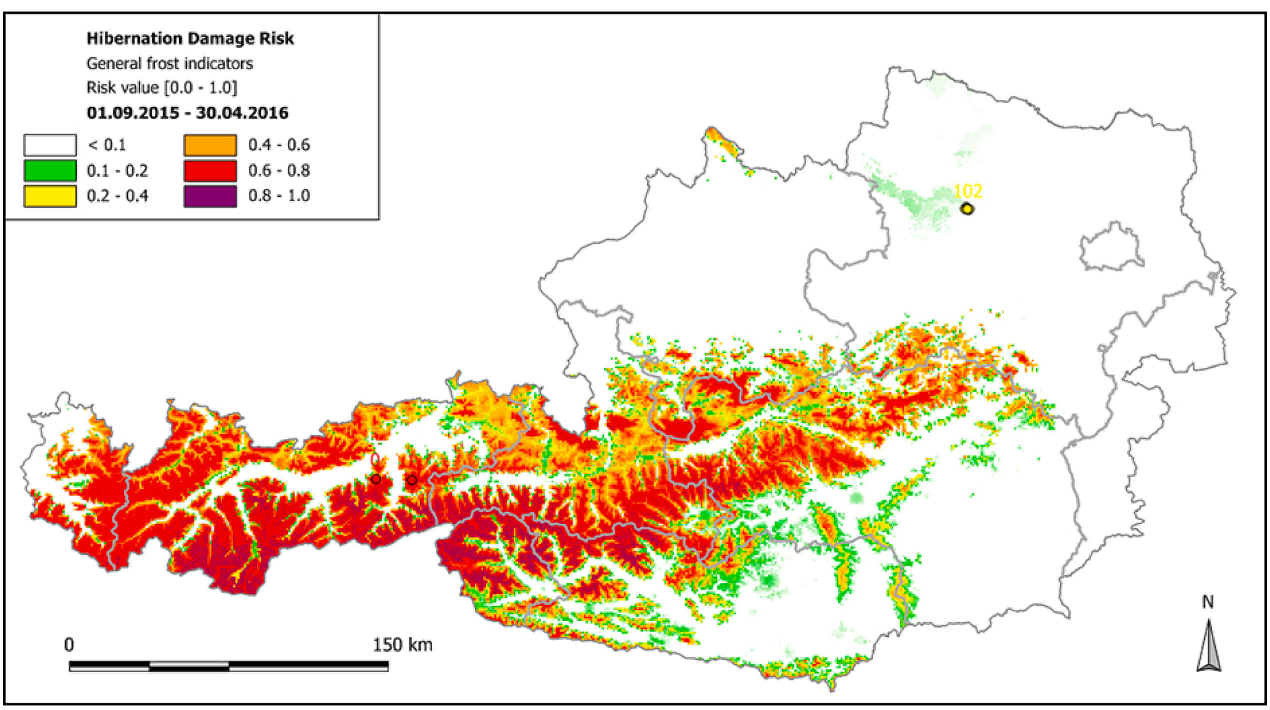

Fig. 6. General overwintering (hibernation) damage risk (Table 4a). Probability of hibernation damage based for winter cereals for whole Austrian domain, regardless of land-use type.

outputs of the soil-crop water balance and phenological model, as described above. All indicators and model outputs are based either on literature or own development where almost all indicators, which indicate crop or impact responses (except Peronospora incubation period), were already calibrated or validated for at least one location or region over the Austrian agricultural regions. We divided the indicators calculated in ARIS into two main groups which are a) crop independent stress and suitability indicators (Table 4a) and b) crop-specific stress and suitability indicators (Table 4b) as follows.

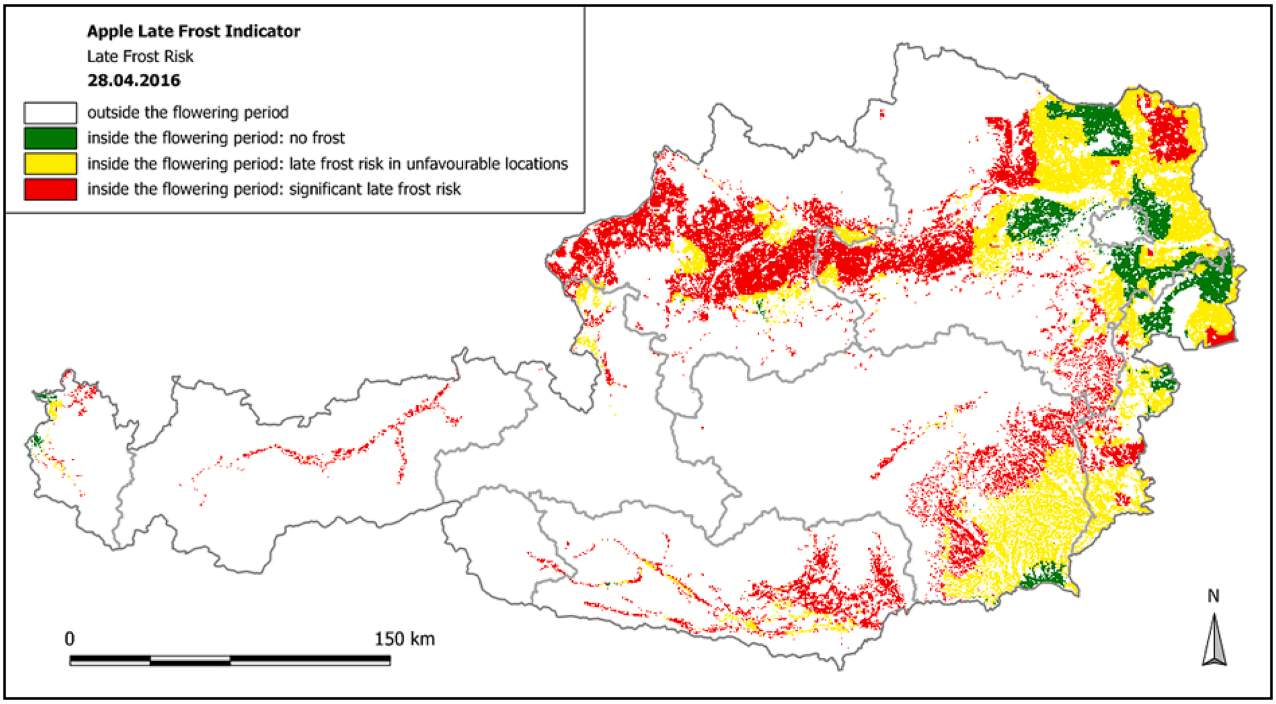

Fig. 7. Daily apple late frost damage risk (Table 4b). Coloured areas represent frost conditions for agricultural land use type (arable land and grasslands) in Austria during the apple flowering period.

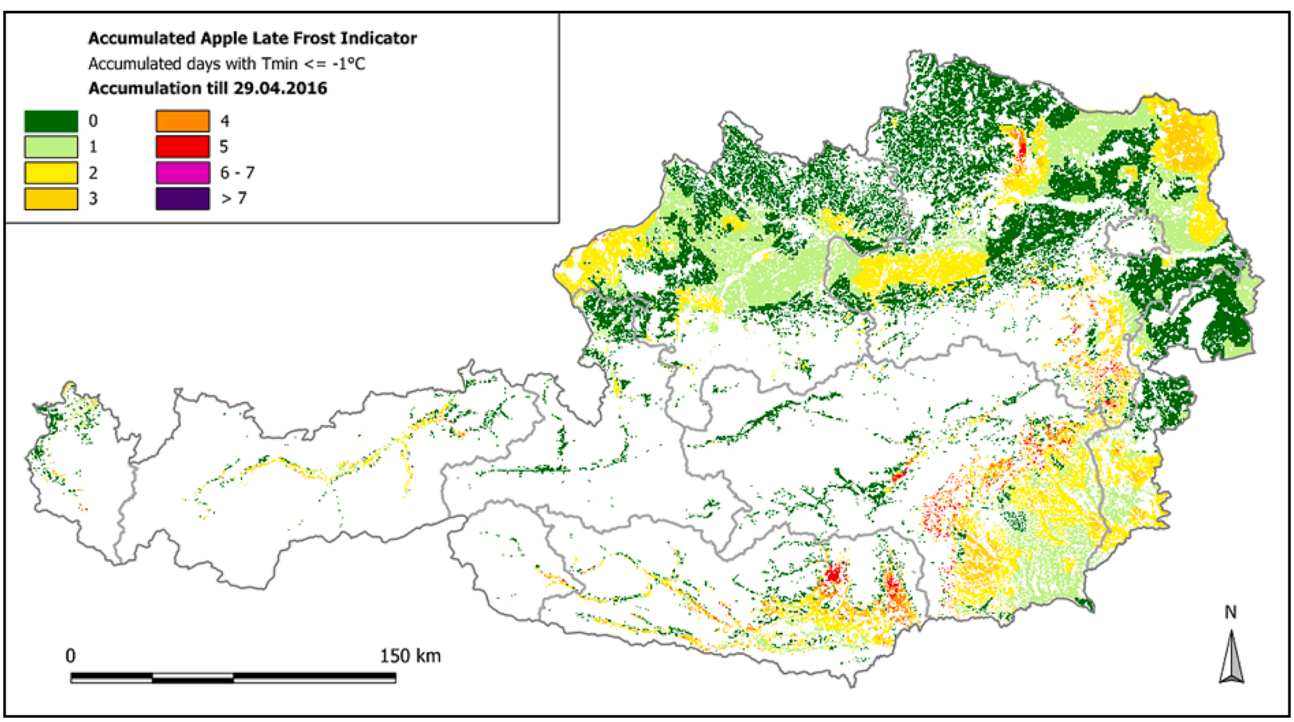

Fig. 8. Accumulated apple late frost damage risk (Table 4b). Calculating the number of days with late frost during apple flowering for agricultural land use type in Austria.

Demonstration examples of spatial ARIS outputs

Hind-casting, monitoring and forecasting of agricultural risks by indicators

Selected computed crop-specific stress and suitability indicators from Tables 4a,b are shown as maps for the Austrian domain (Figs. 3–8). The indicators were computed for corresponding cells in accordance with the implemented land-use model at a spatial resolution of 500 m grid for soil conditions and the gridded input weather data INCA based on 1 × 1 km grid size.

Winter severity is calculated as temperature sum below 0 °C. It is shown in Fig. 3 for the whole domain of Austria for the winter period 2012/2013. As this indicator is only determined by temperature a clear dependence on sea level is obvious, especially expressed over the Alps.

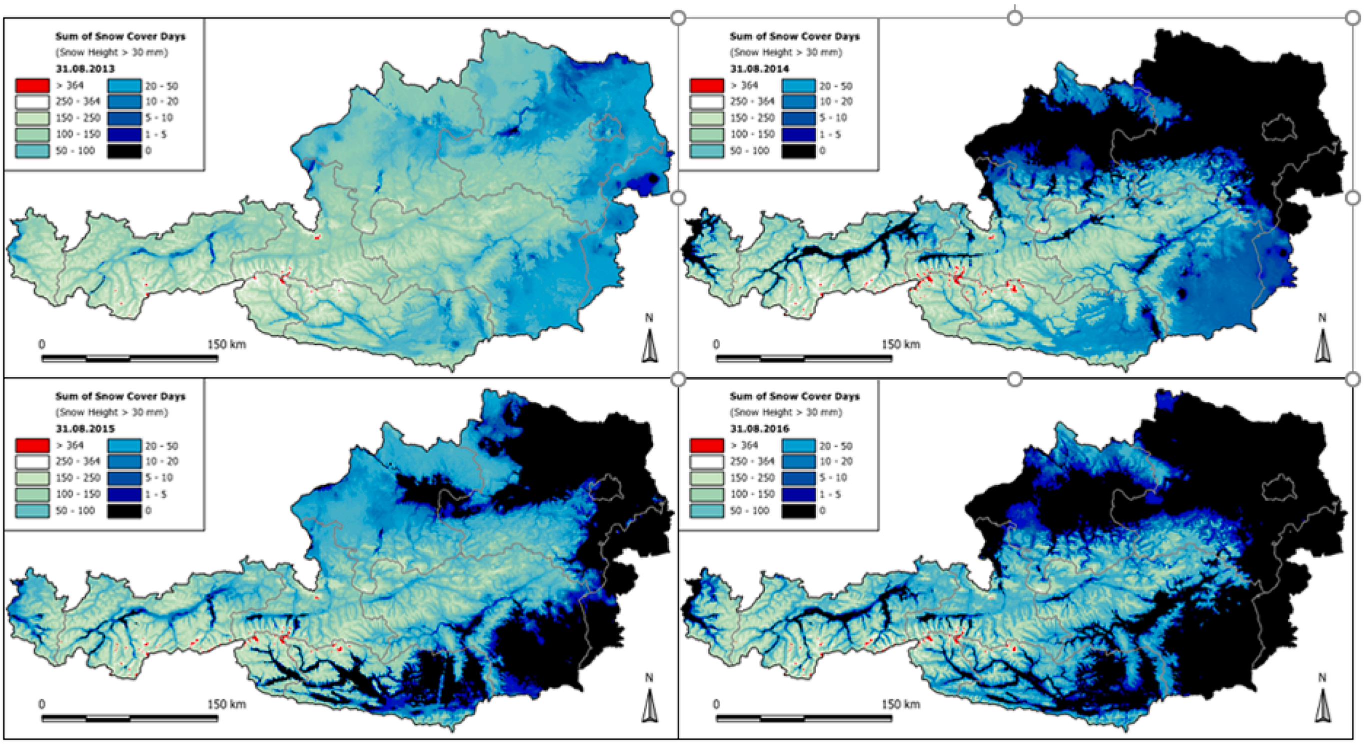

Fig. 9. Spatial expression of the indicator “snow cover” (Table 4a) over 2013–2016 for Austria.

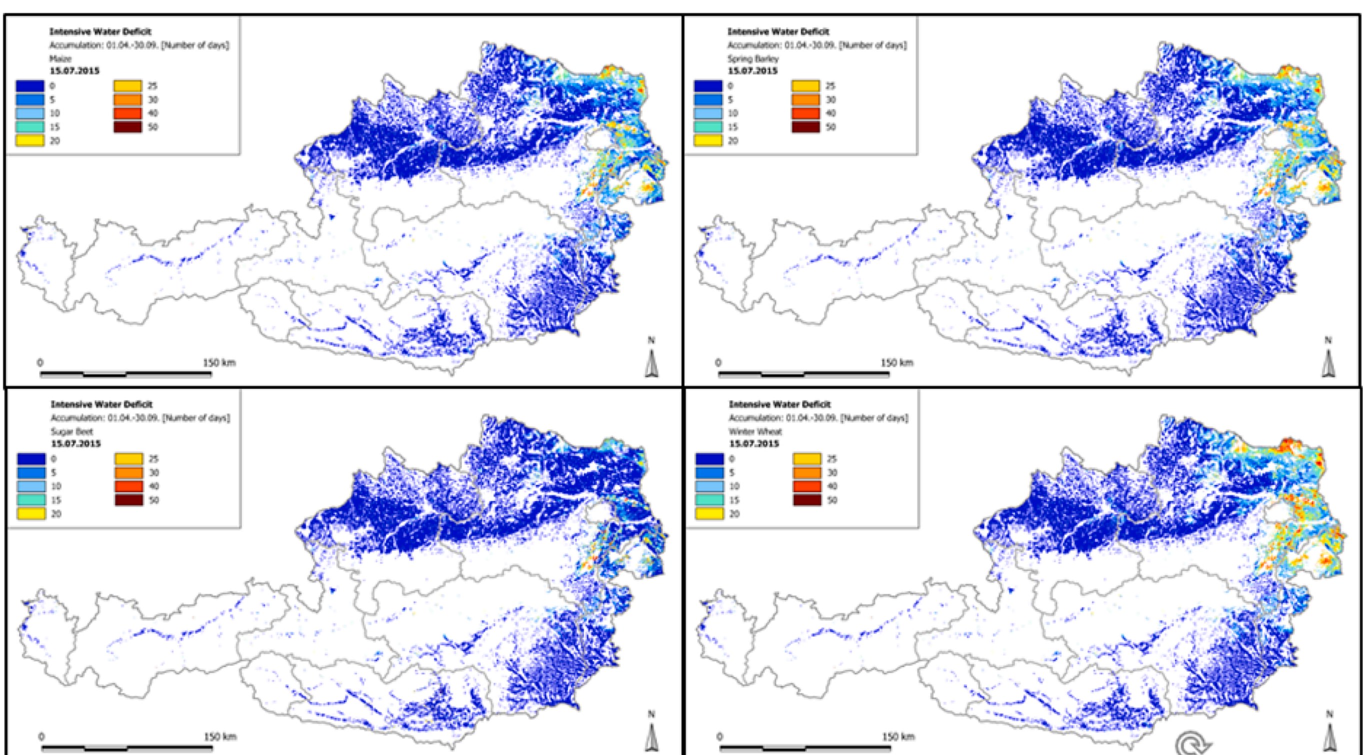

Fig. 10. Spatial expression of the crop specific indicator “intensive water deficit” (Table 4b) for summer 2015 for Austria.

As another example, the indicator for field working days of the arable regions is shown in Fig. 4 for the first two weeks of July 2015, which is a main cereal harvesting period. This indicator is determined by soil top layer (20 cm) moisture, including consideration of precipitation over the past 3 days. In that case, especially in the north-eastern and southern part of Austria unsuitable conditions for harvest or any other fieldwork were present.

The image shows the accumulated days from July 1st to July 15th 2015 (within the accumulation period of July 1st till July 30th) with soil conditions suited for harvesting.

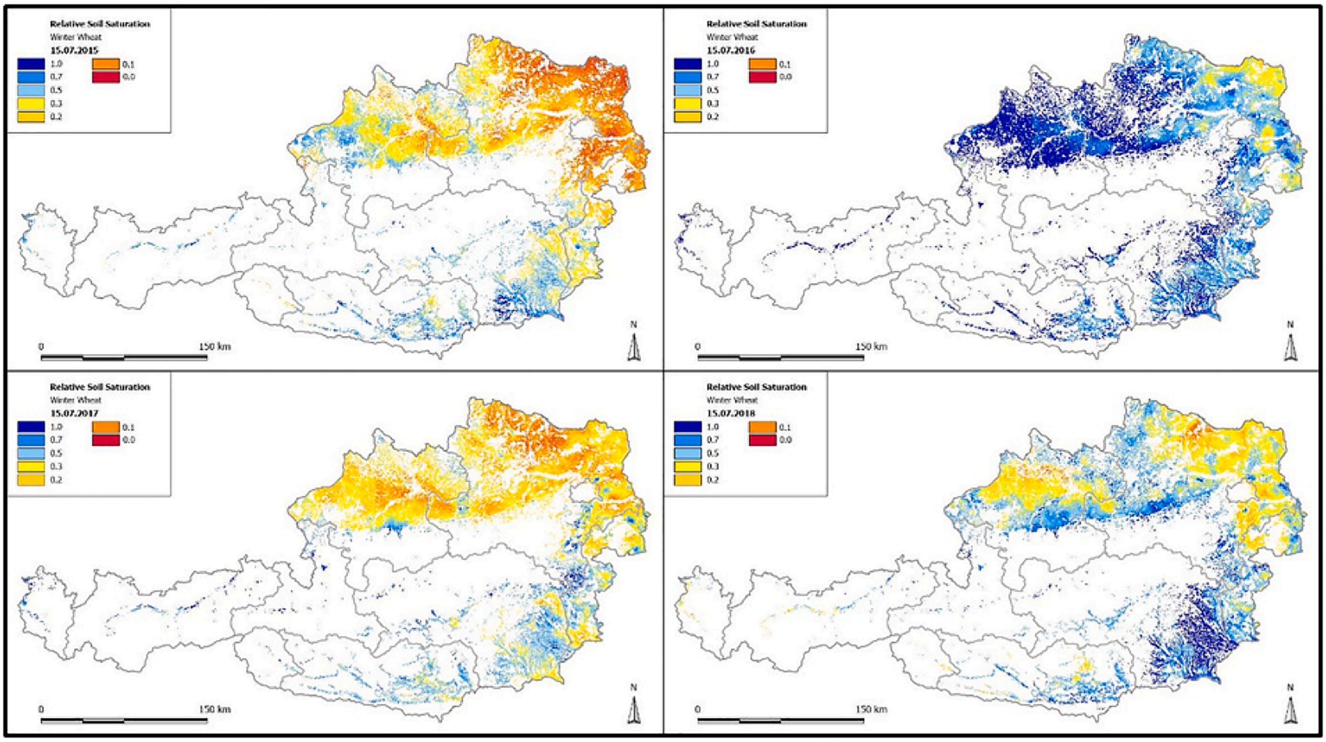

Fig. 11. Spatial expression of soil layer (0-20cm) and crop specific relative soil saturation (Table 4b) for a selected calendar day (15th July) of the years 2015–2018 for Austria.

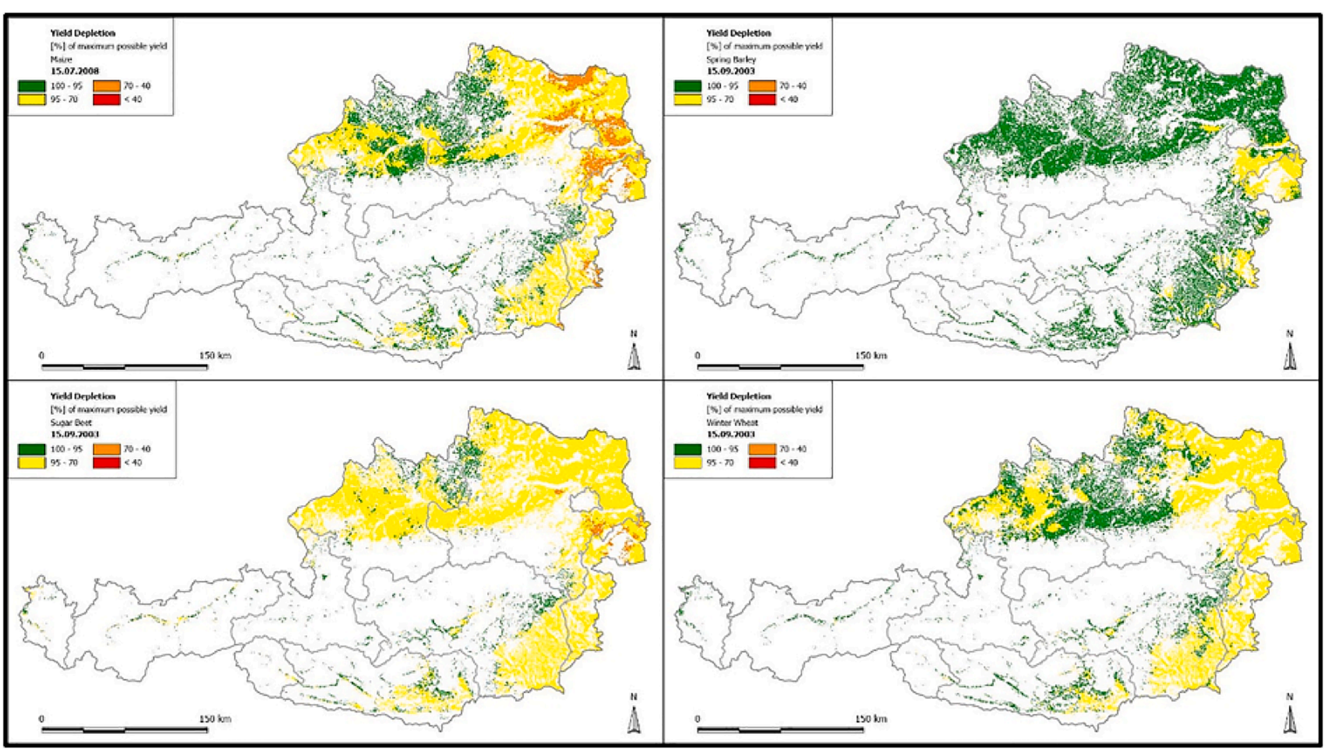

Fig. 12. Spatial expression of the crop specific relative potential yield reduction (Table 4b) at close to the crop specific harvest date for different crops in Austria.

A more and more important effect of climate change on crop production is evolving due to increasing heat days and drought periods. Crop drought stress in ARIS is calculated based on the RSS indicator (Table 4b) limits, where RSS is calculated from the ARIS crop-soil water balance model outputs. A critical factor for all water balance related indicators is the calculated soil layer specific soil water content (SWC) in ARIS. A validation of ARIS against in-situ soil water content measurements showed very good results in a recent study (Thaler et al., 2023, in review).

As an example, we show the heat and drought combining stress

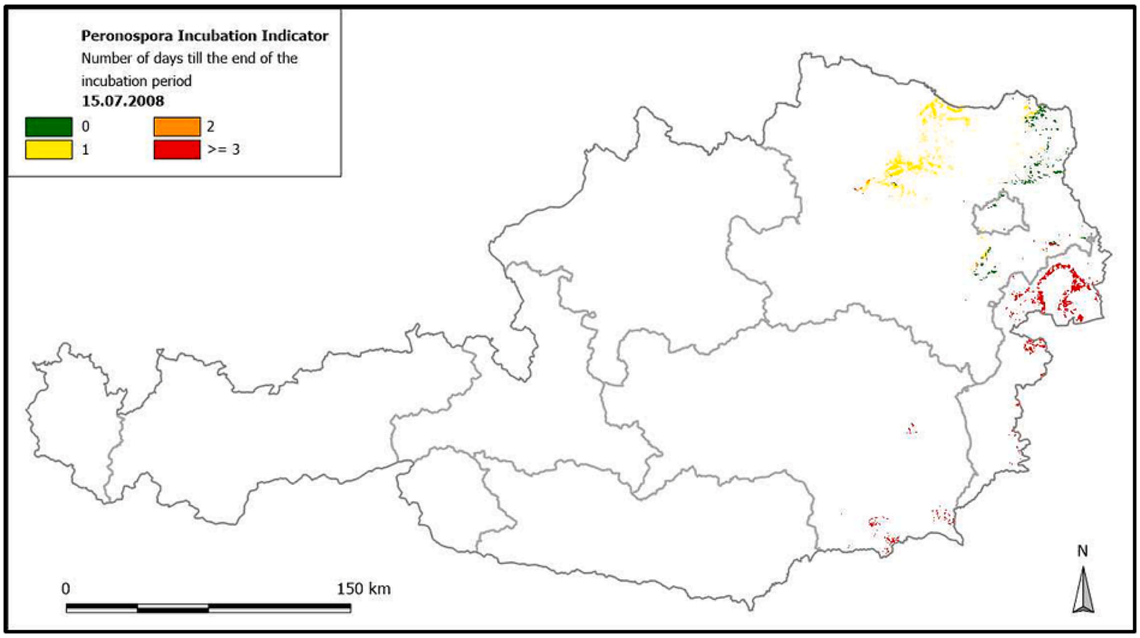

Fig. 13. Peronospora incubation period indicator for vineyard regions in Austria (Table 4b).

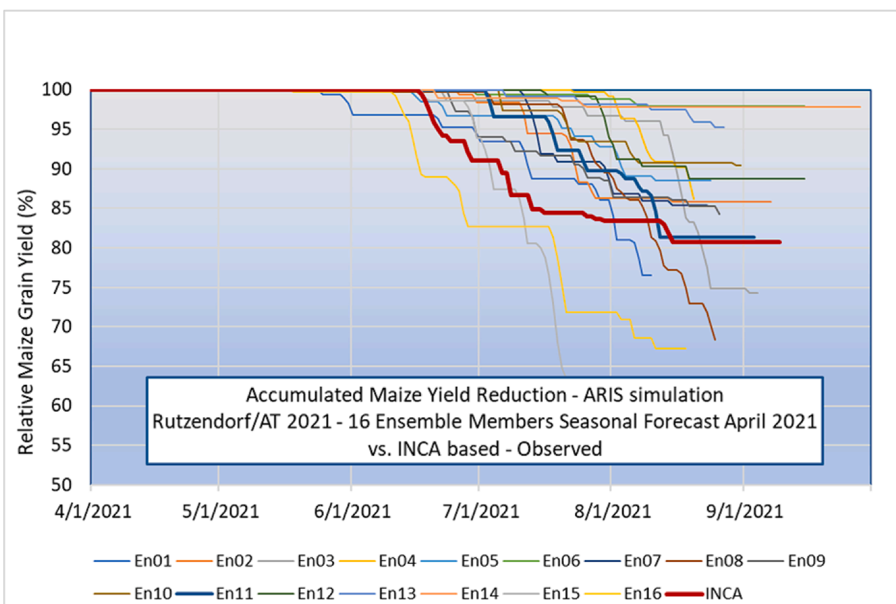

Fig. 14. Accumulated potential relative yield reduction due to combined drought and heat stress on a daily base for grain maize yield at a site in north-eastern Austria (Rutzendorf) based on ARIS predictions from seasonal forecasts vs. INCA-based observed weather.

indicator (Table 4b) for winter wheat for arable regions for the same period of the first 2 weeks in July 2015 as in Fig. 4 in the next figure (Fig. 5). The distribution shows that especially the north-eastern part of Austria was affected by drought and heat stress, which might affect negatively corn filling of winter wheat, while harvest conditions are very suitable.

An indicator for arable field crops overwintering damage risk expressed as a probability (0–1) is presented in Fig. 6 for the winter period 2015/16 for the whole Austrian domain. The Alps are included to highlight the overall (but spatial and temporal variable) sea-level dependence of that indicator, which is combining minimum temperatures and snow cover duration.

An indicator for daily based apple late frost damage risk is shown in Fig. 7. It combines calculated flowering period and early fruit initialisation of apple by a phenological algorithm with below 0 °C and below 1 °C temperature thresholds. The figure shows the day of April 28th, 2016, where strong late frost damages at apple blooms over Austria were recorded.

For the same late frost event as shown in Fig. 7, the accumulated number of days of late frost risk damage using a temperature threshold of −1°C during the calculated apple flowering period is shown in Fig. 8. It shows that both, lowland regions and regions with higher elevations escaped late frost damage due to later (e.g. green area of the northern part of Austria) or earlier flowering (green area of the eastern part of Austria) than at the time of late frost occurrence.

As one of the driving factors for winter severity (see Fig. 3), Fig. 9

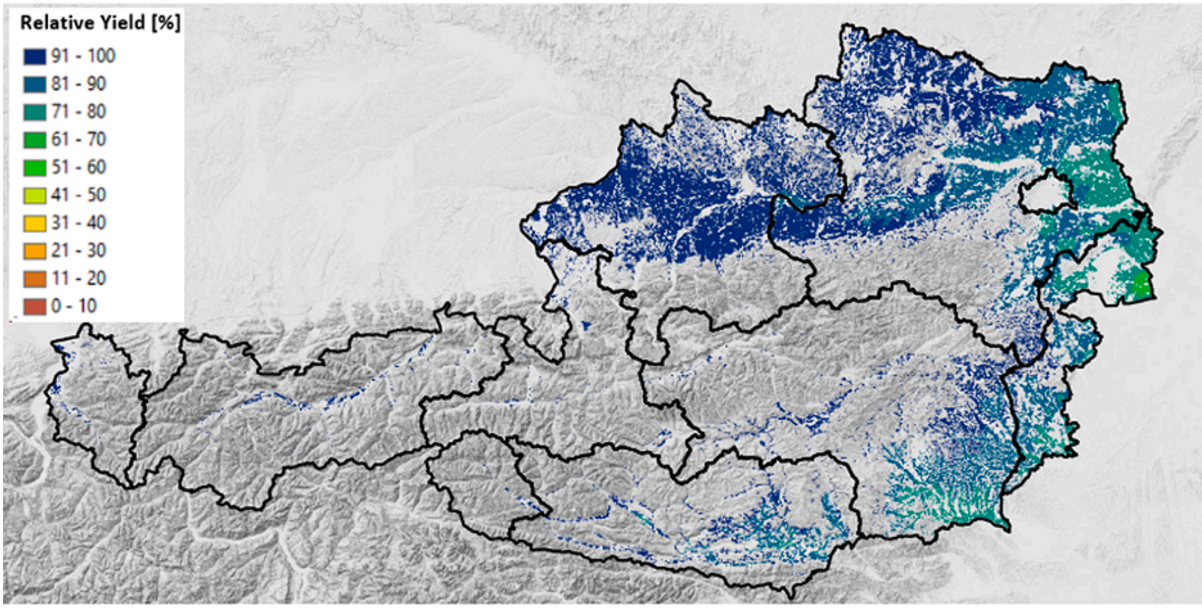

Fig. 15. Relative final potential grain maize yield depletion, based on seasonal weather forecast ensemble member 11 for 2021 (compare Fig. 13) over Austrian arable maize growing regions.

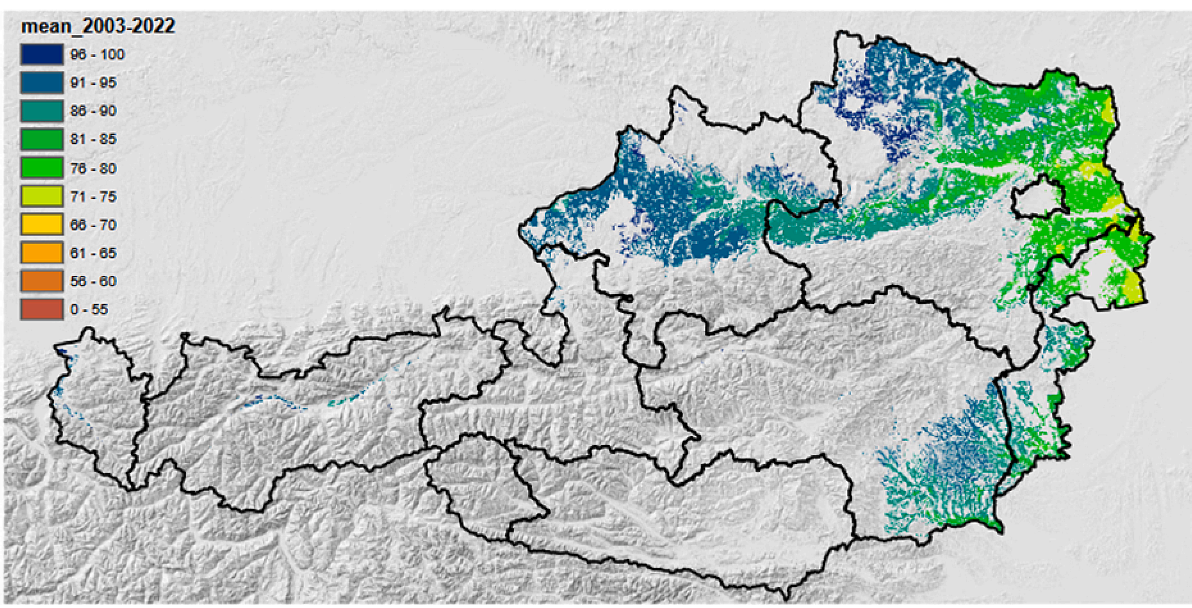

Fig. 16a. Mean maize grain yield depletion due to drought and heat impact over Austria for the period 2003–2022, based on observed weather data.

demonstrates annual comparisons of the indicator "snow cover days" from the years 2013–2016 in the Austrian lowland regions.

An important part of ARIS is the crop-specific calculation of drought indicators. These are expressed as "relative soil saturation", "drought intensity" and "intensive water deficit" indicators (Table 4b).

Fig. 10 shows the indicator "intensive water deficit" for 4 considered crops between April and September 2015. According to the results, especially spring barley and winter wheat were affected by drought stress in the north-eastern part of Austria (which is also the most drought-prone region of Austria).

A further, very relevant output for agricultural practice is the mapping option of the factor RSS (relative soil saturation), which shows the actual daily crop available soil water for pre-defined soil layers (Fig. 11). This application can be considered for use of observation as well as forecasting of agricultural drought.

Based on the agricultural drought indicator RSS (Fig. 11) and heat stress days (combined drought and heat stress indicator, see Fig. 5) a further indicator determining the relative reduction of potential crop yield was implemented, which was calibrated for Austrian climatic and cropping conditions. Fig. 12 shows as an example the yield reduction potential due to drought and heat impact accumulated until a certain date for different years and crops. It can be seen that the relevant impact may differ by crop and crops growing season, region and year. Finally, as an example for spatial expression of an implemented disease risk algorithm (Peronospora for grapewine) Fig. 13 shows Peronospora incubation risk, classified from 0 (no) to 3 (high) for a specific date and year.

ARIS application on short-term to seasonal weather forecasts

ARIS daily weather data inputs need to meet a grid size of 1 km,

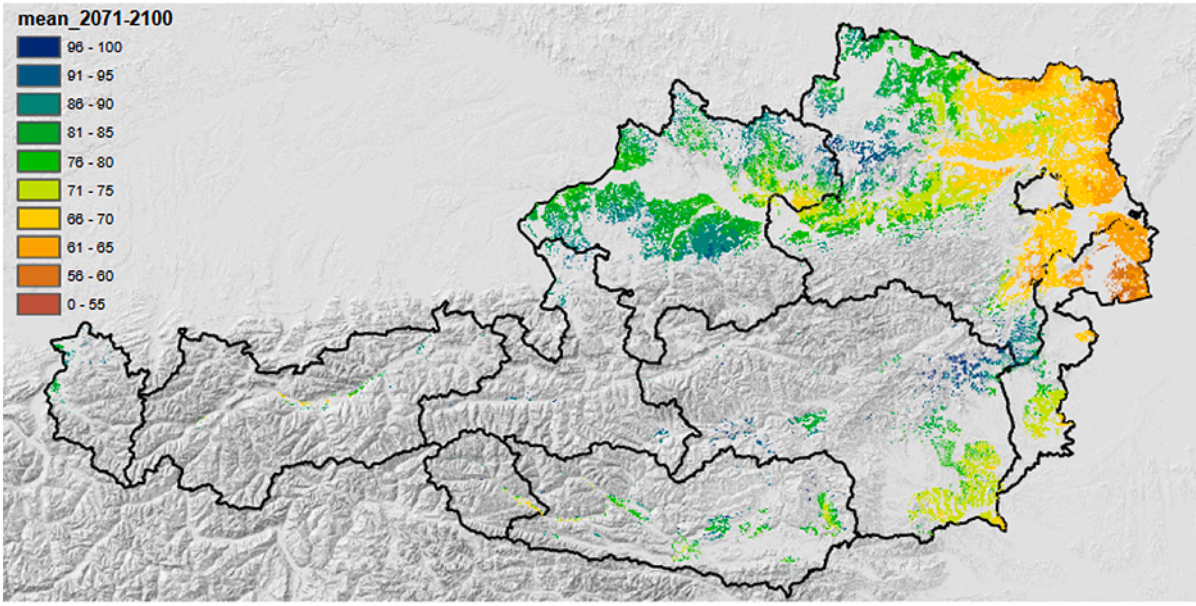

Fig. 16b. Mean maize grain yield reduction due to drought and heat impact over Austria for a selected ÖKS15 climate scenario for the period 2071–2100.

which are available for weather forecasts of NWP models of different lead times in Austria. Fig. 14 shows the example of an ARIS indicator (accumulated maize grain yield depletion from maximum observed crop yield level) for a 16-ensemble member seasonal (7-month) forecast, starting with April 2021 in comparison with INCA based observed weather data for a specific site in eastern Austria (Rutzendorf). In this case, ensemble member 11 shows the best agreement with the INCA-based prediction. In comparison, the spatial expression for whole Austrian arable regions of the final maize grain yield reduction (at harvest) for ensemble member 11 is shown in Fig. 15.

ARIS application for climate scenarios

Similar to weather forecasts ARIS can be applied on climate scenarios, which are downscaled to 1 km grid size and available as daily weather series. Fig. 16 show the multi-year averages of grain maize yield reduction from potential yield level for two time slices, the reference period of INCA-based weather data form 2003–2022 (Fig. 16a) vs. a climate scenario (ÖKS15) period 2071–2100 (Fig. 16b), for all arable regions of Austria. It can be seen that a slight yield reduction potential is visible for that specific climate scenario. It has to be kept in mind that the algorithm was calibrated on current agricultural production technology, so only the climatic impact is expressed.

Discussion on assumptions and limitations

As any model or modelling system, ARIS, consisting mainly of simplified algorithms for calculating suitability and risk indicators for agricultural crop production, has several inherent assumptions and limitations which cause uncertainties in the results. First of all, models in any complexity always represent a simplification of, in our case, ecosystem or environmental processes, caused by several facts, which are 1) uncertainties or knowledge gaps on these processes; 2) unavailability of data which are needed as inputs to models, to calibrate, validate and apply them and 3) the needed technical (IT) capacities to calculate complex processes, especially at larger spatial scales. Thus, simplification is an optimization process in order make environmental modelling systems applicable, e.g. for operational applications on various time periods. However, the more simplification, the more important is the parametrization (calibration) and validation of models, which again needs a good data base for calibration of algorithms, especially in the spatial scale, such as in ARIS. This is especially needed for impact indicators, which assess crop responses, rather than for indicators which calculate just conditions (e.g. pre-defined drought and heat limits or soil water depletion). Here, new high-resolution spatial data sets, such as those derived from remote sensing can enhance the spatial representativeness of certain ARIS indicators (e.g. crop yield depletion) when used for calibration and validation or directly as complementary information source, which is a promising outlook for the further development of ARIS.

It means, such an operational modelling system of various indicators needs to apply a permanent calibration procedure, to improve or ensure representativeness and applicability. For ARIS algorithms, where underlying drivers (such as crop sensitivity and stress tolerance) may change over time, this is a limitation as well as a requirement to ensure the quality of the different spatial–temporal application scales and to address related uncertainties. ARIS is not calculating crop suitability or cropping risks in a complex manner with interacting processes, rather than single indicators, which are only partly linked to each other, such as drought and heat. It delivers a set of indicators which in combination or as a single information can serve stakeholders in the agricultural sector, however, as a decision support tool with clear and understandable messages (e.g. specific crop stress levels or risks). In summary, in order to apply ARIS in an operational way by institutions, IT resources and required skills to operate the system are not a main limitation nowadays anymore, rather than the availability of the relevant required spatial data sets (at 1 km grid scale in our case), including static data such as soil conditions, land use map and DHM as well as gridded weather parameters at a daily time step.

Additionally, for any regional application, the quality assurance, evaluation or new development and integration of any indicators, especially crop impact indicators, need multi-site and multi-year data sets on relevant crop responses.

Conclusions

ARIS (Agricultural Risk Information System) is described and demonstrated for Austrian domain and conditions, using a set of abiotic and biotic weather-related cropping risks or crop growing conditions indicators. The ability to simulate for a large domain grid based agricultural risk indicators in one model run, where past periods do not to be replicated for any update run, offers a wide application potential for different stakeholder needs. The applied grid size of 1 km (0.5 km for soil conditions), however, set limitations for applications at field level precision farming, where other approaches can better reflect smaller scale variations. The adaptability to different regions and their agroecosystem conditions as well as extension or modifications in the set of applied indicators to adapt to stakeholder demand, is an important feature of the ARIS system. It has to be kept in mind, however, that a suitable spatial grid-based input data set, especially for weather and soil parameters, is crucial for the local performance of simulation results beside the capability to calibrate and validate the implemented crop response or risk indicators to regional/local conditions when new spatial data sets (e.g. crop development parameters derived from remote sensing among others) become available.

Funding

This research received no external funding except the acknowledged research grant.

Statement

The authors did not use any generative AI and AI-assisted technologies in the writing process of this manuscript.

CRediT authorship contribution statement

Josef Eitzinger: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Voiko Daneu:** Writing – original draft, Visualization, Software, Methodology. **Gerhard Kubu:** Visualization, Data curation. **Sabina Thaler:** Validation, Investigation, Data curation. **Mirek Trnka:** Methodology. **Andreas Schaumberger:** Methodology. **Stefan Schneider:** Writing – original draft, Data curation. **Thi Mai Anh Tran:** Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Josef Eitzinger reports financial support was provided by Univ. für Bodenkultur Wien.

Data availability

The authors do not have permission to share data.

Acknowledgments

This study was conducted with the support of projects AgroDroughtAustria, COMBIRISK and AGROFORECAST of the Austrian Climate Research Programme (ACRP) as well as of the project AdAgriF of the Global Change Research Centre Academy of Sciences of the Czech Republic. We would like to acknowledge support of Jan Balek (CzechGlobe) who assisted with development of some of the ARIS algorithms.

References

Abramoff, R.Z., Ciais, P., Zhu, P., Hasegawa, T., Wakatsuki, H., Makowski, D., 2023. Adaptation strategies strongly reduce the future impacts of climate change on simulated crop yields. Earth's Future 11 (4). https://doi.org/10.1029/2022EF003190.

Allen, G. R., Pereira, S. L., Raes, D., Smith, M., 1998. Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements. FAO Irrigation and drainage paper 56. Rome, Italy: Food and Agriculture Organization of the United Nations. ISBN 92-5-104219-5.

APCC, 2014. Österreichischer Sachstandsbericht Klimawandel 2014 (AAR14). Austrian Panel on Climate Change (APCC). 1096 pp., Verlag der Österreichischen Akademie der Wissenschaften, Wien, Österreich.

Baekelandt, A., Saltenis, V.L.R., Nacry, P., Malyska, A., Cornelissen, M., Nanda, A.K., Nair, A., Rogowsky, P., Pauwels, L., Muller, B., Collén, J., Blomme, J., Pribil, M., Scharff, L.B., Davies, J., Wilhelm, R., Rolland, N., Harbinson, J., Boerjan, W., Murchie, E.H., Burgess, A.J., Cohan, J.-P., Debaeke, P., Thomine, S., Inzé, D., Lankhorst, R.K., Parry, M.A.J., 2023. Paving the way towards future-proofing our crops. Food Energy Secur. 12 (3) https://doi.org/10.1002/fes3.441.

BFW, 2023. ebod, https://bfw.ac.at/rz/bfwcms2.web?dok=7066 (accessed 16 March 2024).

Blümel, S., Eitzinger, J., Gruber, B., Gatterer, M., Altenburger, J., Hausdorf, H., 2020. Influence of weather variables on the first seasonal occurrence of the grape berry moths Eupoecilia Ambiguella (Lepidoptera: Tortricidae) and Lobesia Botrana (Lepidoptera: Tortricidae) in a case study region in Austria. MITT KLOSTERNEUBURG 70 (2), 115–128.

Bras, T.A., Seixas, J., Carvalhais, N., Jägermeyr, J., 2021. Severity of drought and heatwave crop losses tripled over the last five decades in Europe. Environ. Res. Lett. 16 (6) https://doi.org/10.1088/1748-9326/abf004.

Chimani, B., Matulla, C., Hiebl, J., Schellander-Gorgas, T., Maraun, D., Mendlik, T., Eitzinger, J., Kubu, G., Thaler, S., 2020. Compilation of a guideline providing comprehensive information on freely available climate change data and facilitating their efficient retrieval. Clim. Serv. 19, 100179.

Dornik, A., Cheţan, M.A., Crişan, T.A., Heciko, R., Gora, A., Drăguţ, L., Panagos, P., 2024. Geospatial evaluation of the agricultural suitability and land use compatibility in Europe's temperate continental climate region. Int. Soil Water Conserv. Res. 10.1016/j.iswcr.2024.01.002.

EEA, 2023. CORINE Land Cover (CLC), https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-corine (accessed 16 March 2024).

Eitzinger, J., Daneu, V., Bodner, G., Kubu, G., Loiskandl, W., Macaigne, P., Thaler, S., Schaumberger, A., Wittmann, C., Weidle, F., Kann, A., Murer, E., Krammer, C., Trnka, M., Hayes M. Drought monitoring system for Austrian agriculture – AgroDroughtAustria. BOKU-Met Report 25, ISSN 1994-4179. ISSN 1994-4187 (online) [Internet] [Forschungsbericht (extern. Auftraggeber)]. 2016 p. 89. Available from: https://meteo.boku.ac.at/report/BOKU-Met_Report_25_online.pdf (accessed 16 March 2024).

Eitzinger, J., Thaler, S., Schmid, E., Strauss, F., Ferrise, R., Moriondo, M., Bindi, M., Palosuo, T., Rotter, R., Kersebaum, K.C., Olesen, J.E., Patil, R.H., Saylan, L., Caldag, B., Caylak, O., 2013. Sensitivities of crop models to extreme weather conditions during flowering period demonstrated for maize and winter wheat in Austria. J. Agric. Sci. 151 (6), 813–835. https://doi.org/10.1017/s0021859612000779.

Elsgaard, L., Børgesen, C.D., Olesen, J.E., Siebert, S., Ewert, F., Peltonen-Sainio, P., Rötter, R.P., Skjelvåg, 2012. Shifts in comparative advantages for maize, oat and wheat cropping under climate change in Europe. Food Addit. Contam. - Part A 29 (10), 1514–1526. https://doi.org/10.1080/19440049.2012.700953.

Firanj Sremac, A., Lalic, B., Eitzinger, J., and Schneider, S., 2021. Modeling phenology of the Central European apple: The seasonal forecast application perspective, EMS Annual Meeting 2021, online, 6–10 Sep 2021, EMS2021-123, 10.5194/ems2021-123, 2021.

Franke, J.A., Müller, C., Elliott, J., Ruane, A.C., Jägermeyr, J., Snyder, A., Dury, M., Falloon, P.D., Folberth, C., François, L., Hank, T., Izaurralde, R.C., Jacquemin, I., Jones, C., Li, M., Liu, W., Olin, S., Phillips, M., Pugh, T.A.M., Reddy, A., Williams, K., Wang, Z., Zabel, F., Moyer, 2020. The GGCMI Phase 2 emulators: global gridded crop model responses to changes in CO_2, temperature, water, and nitrogen (version 1.0). Geosci. Model Dev. 13, 3995–4018. https://doi.org/10.5194/gmd-13-3995-2020.

Ghaemi, E., Foelsche, U., Kann, A., Fuchsberger, J., 2021. Evaluation of Integrated Nowcasting through Comprehensive Analysis (INCA) precipitation analysis using a dense rain-gauge network in southeastern Austria. Hydrol. Earth Syst. Sci. 25 (8), 4335–4356. https://doi.org/10.5194/hess-25-4335-2021.

Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., Stoffel, M., 2014. 21st century climate change in the European Alps–a review. Sci. Total Environ 493, 1138–1151. https://doi.org/10.1016/j.scitotenv.2013.07.050.

Gourdji, S.M., Sibley, A.M., Lobell, D.B., 2013. Global crop exposure to critical high temperatures in the reproductive period: historical trends and future projections. Environ. Res. Lett. 8 (2).

Haiden, T., Kann, A., Wittmann, C., Pistotnik, G., Bica, B., Gruber, C., 2011. The Integrated Nowcasting through Comprehensive Analysis (INCA) system and its validation over the eastern Alpine region. Weather Forecast. 26, 166–183. https://doi.org/10.1175/2010WAF2222451.1.

Herrera-Lormendez, P., Douville, H., Matschullat, J., 2023. European summer synoptic circulations and their observed 2022 and projected influence on hot extremes and dry spells. Geophys. Res. Lett. 50, e2023GL104580 https://doi.org/10.1029/2023GL104580.

Hlavinka, P., Trnka, M., Balek, J., Semeradova, D., Hayes, M., Svoboda, M., Eitzinger, J., Mozny, M., Fischer, M., Hunt, E., Zalud, Z., 2011. Development and evaluation of the SoilClim model for water balance and soil climate estimates. Agr. Water Manage 98 (8): 1249-1261.

Huglin, P., 1978. Nouveau mode d'e´valuation des possibilite´s he´liothermiques de la vigne. Comptes Rendus de l'Acade´mie d'Agriculture, France, 1117–1126.

IPCC, 2019. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

Kann, A., Wittmann, C., Bica, B., Wastl, C., 2015. On the impact of NWP model background on very high–resolution analyses in complex terrain. Weather Forecast. 30 (4), 1077–1089. https://doi.org/10.1175/WAF-D-15-0001.1.

Kirchner, M., Schmidt, J., Kindermann, G., Kulmer, V., Mitter, H., Prettenthaler, F., Rüdisser, J., Schauppenlehner, T., Schönhart, M., Strauss, F., Tappeiner, U., Tasser, E., Schmid, E., 2015. Ecosystem services and economic development in

Austrian agricultural landscapes — The impact of policy and climate change scenarios on trade-offs and synergies. Ecol. Econ. 109, 161–174. https://doi.org/10.1016/j.ecolecon.2014.11.005.
Koppensteiner, L., Diry, A., Schneider, B., Weilner, E., 2017. Influence of weather risks on selected crops of selected weather extremes – Indicators for overwintering damage on Winter Rape, Winter Barley, Winter Wheat and Winter Rye in Austria. Bachelor thesis, BOKU University, Vienna (unpublished results).
Lobell, D.B., Cassman, K.G., Field, C.B., 2009. Crop yield gaps: Their importance, magnitudes, and causes. Annu. Rev. Env. Resour. 34 (1), 179–204. https://doi.org/10.1146/annurev.environ.041008.093740.
Maiorano, A., Martre, P., Asseng, S., Ewert, F., Müller, C., Rötter, R.P., Ruane, A.C., Semenov, M.A., Wallach, D., Wang, E., Alderman, P.D., Kassie, B.T., Biernath, C., Basso, B., Cammarano, D., Challinor, A.J., Doltra, J., Dumont, B., Eyshi Rezaei, E., Gayler, S., Kersebaum, K.C., Kimball, B.A., Koehler, A.K., Liu, B., O'Leary, G.J., Olesen, J.E., Ottman, M.J., Priesack, E., Reynolds, M., Stratonovitch, P., Streck, T., Thorburn, J., Waha, K., Wall, G.W., White, J.W., Zhao, Z., Zhu, Y., 2017. Crop model improvement reduces the uncertainty of the response to temperature of multi-model ensembles. Field Crop Res. 202, 5–20. https://doi.org/10.1016/j.fcr.2016.05.001.
Marin, D., 2021. Evaluation of Multi-Level Methodical Soil Moisture Measurements: Agricultural Application for Spatial Variability Detection. Master thesis; BOKU University, Vienna & Lincoln University, New Zealand. https://permalink.obvsg.at/bok/AC16418567 (accessed 16 March 2024).
Marteau-Bazouni, M., Jeuffroy, M.-H., Guilpart, N., 2024. Grain legume response to future climate and adaptation strategies in Europe: A review of simulation studies. Eur. J. Agron. 153 https://doi.org/10.1016/j.eja.2023.127056.
Metzger, M.J., Bunce, R.H.G., Jongman, R.H.G., Mücher, C.A., Watkins, J.W., 2005. A climatic stratification of the environment of Europe. Glob. Ecol. Biogeogr. 14 (6), 549–563. https://doi.org/10.1111/j.1466-822X.2005.00190.x.
Mihailovic, D.T., Koci, I., Lalic, B., Arsenic, I., Radlovic, D., Balaz, J., 2001. The main features of BAHUS–biometeorological system for messages on the occurrence of diseases in fruits and vines. Environ. Model Softw. 16, 691–696. https://doi.org/10.1016/S1364-8152(01)00032-9.
Murer, E., Wagenhofer, J., Aigner, F., Pfeffer, M.,2004. Die nutzbare Feldkapazität der mineralischen Böden der landwirtschaftlichen Nutzfläche Österreichs. In Bundesamt für Wasserwirtschaft (eds.): Schriftreihe BAW, 20, Bundesamt für Wasserwirtschaft, Institut für Kulturtechnik und Bodenwasserhaushalt, Petzenkirchen, 72-78.
Murer, E., 2009. Überprüfung und Verbesserung der Pedotransferfunktion zur Ermittlung der Wasserspeicherfähigkeit im Boden, Abschlussbericht, Bundesamt für Wasserwirtschaft, Institut für Kulturtechnik und Bodenwasserhaushalt, Petzenkirchen, 54 S.
Olesen, J.E., Trnka, M., Kersebaum, K.C., Skjelvåg, A.O., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J., Micale, F., 2011. Impacts and adaptation of European crop production systems to climate change. Eur. J. Agron. 34 (2), 96–112. https://doi.org/10.1016/j.eja.2010.11.003.
Řehoř, J., Brázdil, R., Trnka, M., Balek, J., 2024. Flash droughts in Central Europe and their circulation drivers. Clim. Dyn. 62, 1107–1121. https://doi.org/10.1007/s00382-023-06964-8.
Rezaei, E.E., Siebert, S., Ewert, F., 2015. Intensity of heat stress in winter wheat—phenology compensates for the adverse effect of global warming. Environ. Res. Lett. 10 (2) https://doi.org/10.1088/1748-9326/10/2/024012.
Rötter, R.P., Carter, T.R., Olesen, J.E., Porter, J.R., 2011. Crop–climate models need an overhaul. Nat. Clim. Chang. 1 (4), 175–177. https://doi.org/10.1038/nclimate1152.
Schaumberger, A., 2011. Räumliche Modelle zur Vegetations- und Ertragsdynamik im Wirtschaftsgrünland. Dissertation, Technische Universität Graz, Institut für Geoinformatik, 264 S.
Schönhart, M., Mitter, H., Schmid, E., Heinrich, G., Gobiet, A., 2014. Integrated analysis of climate change impacts and adaptation measures in Austrian Agriculture, German. J. Agric. Econ. 63 (03), 156–176. https://doi.org/10.22004/ag.econ.253157.
Tebaldi, C., Hayhoe, K., Arblaster, J.M., Meehl, G.A., 2006. Going to the Extremes. Clim. Change 79 (3), 185–211. https://doi.org/10.1007/s10584-006-9051-4.
Thaler, S., Eitzinger, J., Trnka, M., Dubrovsky, M., 2012. Impacts of climate change and alternative adaptation options on winter wheat yield and water productivity in a dry climate in Central Europe. J. Agric. Sci. 150 (5), 537–555. https://doi.org/10.1017/s0021859612000093.
Thaler, S., Eitzinger, J., Kubu, G., Marin, D., Vecchiotti, F., Vreugdenhil, M., Wagner, W. Comparison of different methods of top soil layer water content estimation considering different spatial scales. Unpublished results.
Trnka, M., Kocmánková, E., Balek, J., Eitzinger, J., Ruget, F., Formayer, H., Hlavinka, P., Schaumberger, A., Horáková, V., Možný, M., 2010. Simple snow cover model for agrometeorological applications. Agric. For. Meteorol. 150, 1115–1127.
Trnka, M., Olesen, J.E., Kersebaum, K.C., Skjelvag, A.O., Eitzinger, J., Seguin, B., Peltonen-Sainio, P., Orlandini, S., Dubrovsky, M., Hlavinka, P., Balek, J., Eckersten, H., Cloppet, E., Calanca, P., Rotter, R., Gobin, A., Vucetic, V., Nejedlik, P., Kumar, S., Lalic, B., Mestre, A., Rossi, F., Alexandrov, V., Kozyra, J., Schaap, B., Zalud, Z., 2011. Agroclimatic conditions in Europe under climate change. Glob. Chang. Biol. https://doi.org/10.1111/j.1365-2486.2011.02396.x.
Trnka, M., Kersebaum, K.C., Eitzinger, J., Hayes, M., Hlavinka, P., Svoboda, M., Dubrovsky, M., Semeradova, D., Wardlow, B., Pokorny, E., Mozny, M., Wilhite, D., Zalud, Z., 2013. Consequences of climate change for the soil climate in Central Europe and the central plains of the United States. Clim. Change 120 (1), 405–418. https://doi.org/10.1007/s10584-013-0786-4.
Trnka, M., Rotter, R.P., Ruiz-Ramos, M., Kersebaum, K.C., Olesen, J.E., Zalud, Z., Semenov, M.A., 2014. Adverse weather conditions for European wheat production will become more frequent with climate change. Nat. Clim. Chang. 4 (7), 637–643. https://doi.org/10.1038/Nclimate2242.
Trnka, M., Hlavinka, P., Mozny, M., Semeradova, D., Stepanek, P., Balek, J., Bartosova, L., Zahradnicek, P., Blahova, M., Skalak, P., Farda, A., Hayes, M., Svoboda, M., Wagner, W., Eitzinger, J., Fischer, M., Zalud, Z., 2020. Czech Drought Monitor System for monitoring and forecasting agricultural drought and drought impacts. Int. J. Climatol. 40 (14), 5941–5958.
Webber, H., Martre, P., Asseng, S., Kimball, B., White, J., Ottman, M., Wall., G.W., De Sanctis, G., Doltra, J., Grant, R., Kassie, B., Maiorano, A., Olesen, J.E., Ripoche, D., Eyshi Rezaei, E., Semenov, M.A., Stratonovitch, P., Ewert, F., 2017. Canopy temperature for simulation of heat stress in irrigated wheat in a semi-arid environment: A multi-model comparison. Field Crops Res. 202, 21-35. 10.1016/j.fcr.2015.10.009.
Yue, Y., Zhang, P., Shang, Y., 2019. The potential global distribution and dynamics of wheat under multiple climate change scenarios. Sci. Total Environ. 688 https://doi.org/10.1016/j.scitotenv.2019.06.153.
Zhao, J., Bindi, M., Eitzinger, J., Ferrise, R., Gaile, Z., Gobin, A., Holzkämper, A., Kersebaum, K.-C., Kozyra, J., Kriaučiūnienė, Z., Loit, E., Nejedlik, P., Nendel, C., Niinemets, Ü., Palosuo, T., Peltonen-Sainio, P., Potopová, V., Ruiz-Ramos, M., Reidsm,a P., Rijk, B., Trnka, M., van Ittersum, M.K., Olesen, J., 2022. Priority for climate adaptation measures in European crop production systems. Eur. J. Agron., 138. 10.1016/j.eja.2022.126516.