Diagrams for local crop climate and weather risk analysis, monitoring, and prediction

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Abstract

The meteoblue crop risk diagrams are a novel way to combine climate, weather, and crop data to (1) assess local crop-specific climate risk based on weather event frequency in a suitably chosen reference period, and (2) indicate local crop-specific weather risk during a crop's growing season based on the medium range and seasonal weather forecast. All related information is presented concisely such that risk to crops can be quickly assessed, different locations, seasons, and crops can be easily compared, and options for action can be quickly evaluated.

Figure 1 summarises a local crop climate risk analysis for three different crops at the same location. This information can be used for decisions such as which crops or crop varieties to choose for a particular region.

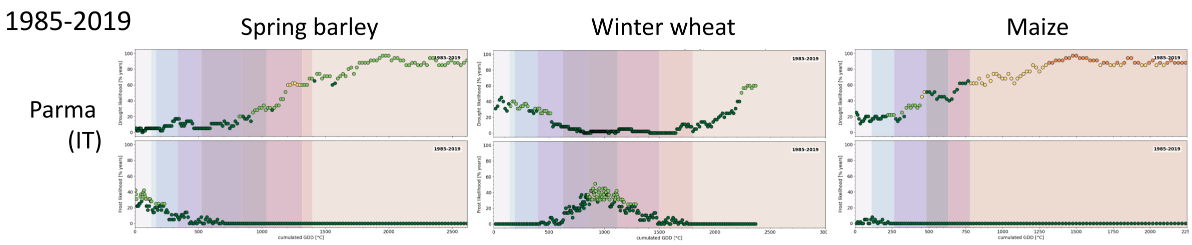

Figure 1: Local drought risk (top) and frost risk (bottom) near Parma, Italy. Vertical bands indicate growth stages as a function of growing degree days, dots represent the likelihood of drought or frost for the period from 1985 to 2019, and dot colour denotes the risk to the crop. The risk is low for winter wheat and high for maize. With a similar likelihood of drought as for maize, the risk for spring barley is medium. Further explanations in the text.

Figure 2 indicates in-season local crop-specific risk from drought at the time the diagram is generated ("Today"), based on available soil water. The blue curve shows available soil water with respect to GDD from planting to Today. The magenta and tan curves respectively show the 7-day and seasonal forecasts for available soil water. Available soil water curves from two past reference periods are included for comparison. The background indicates the impact of low soil water availability on the crop in its growth phases. This diagram supports operational decisions such as when to plant, fertilize, irrigate, etc.

The diagrams can be retrieved from meteoblue via calls to an API (application programming interface) implemented as web services. When calling the API, users can supply their own parameters for weather events and crops to tailor the analysis to their specific local conditions. The API call specification is not in scope for in this paper.

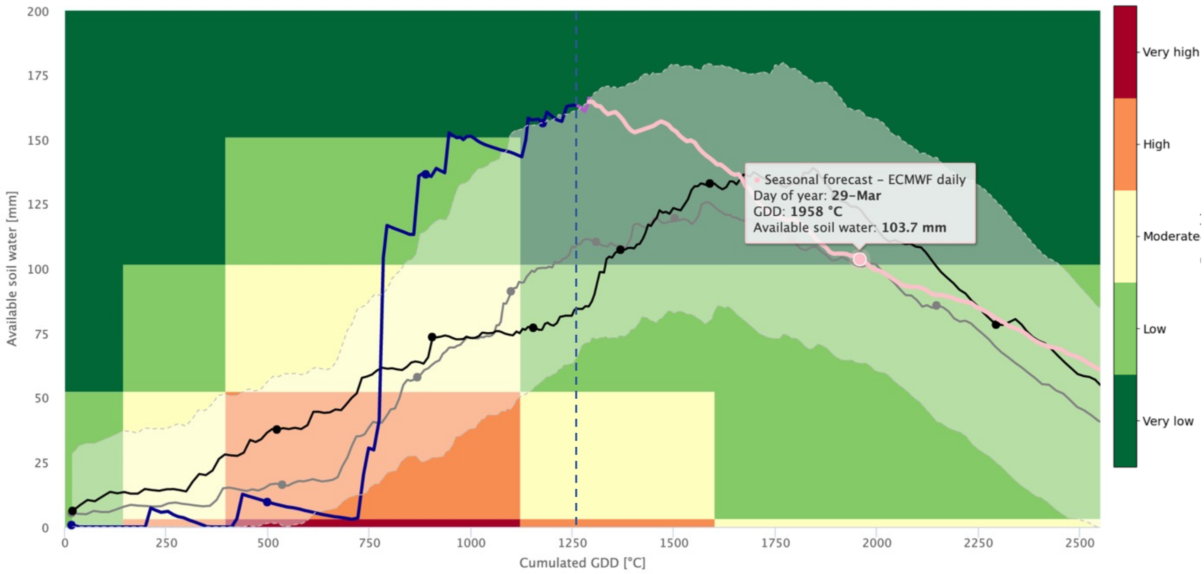

Figure 2: Monitoring (blue curve) and prediction (magenta and tan curves) of available soil water at the time when the diagram is generated ("Today", dashed vertical line). Crop-specific impact of low soil water availability at different growth stages is indicated by the background colours.

1. Introduction

Climate change is affecting agriculture in many European regions and world-wide (Bindi, 2011) (Trnka M., 2016) (Kahiluoto H., 2019). Scope of this work is to combine local climate analysis and weather forecasts to help agricultural agencies and farmers to mitigate climate change impact by making the information available in a form suitable for informed decision making.

Agricultural planning and operations require decision making under largely weather-related uncertainty. This requires to quickly evaluate different options, trading off many interdependent factors, particularly the influence of weather on plant development. Information needs to be presented in quick-to-read informative diagrams for quick assessment and easy comparison.

The main technical objectives of this work are:

- Link the weather events to crop-specific risk with, initially, simple statistics and crop growth stage parameters.
- Develop innovative ways to simultaneously analyse the crop specific risk of weather events over different locations and time horizons (past, present and future).

To design good solutions, it is important to understand what decisions need to be supported. Among the key decisions that the present work aims to support are:

1. Strategic, long-term decisions: assess risk, select a location, select a crop, determine what additional information is required
2. Operational decisions – pre-planting: last-minute decisions on which crop varieties to plant, how early or late to plant the crop, intervention planning for the upcoming season
3. Operational decisions – post planting: weekly intervention planning

The paper first describes the available data, followed be the description of our approach and some examples. It then lists the data that users can supply to increase the accuracy or the analysis. We conclude by listing possible improvements.

2. Weather and crop-specific risk

Our method provides a crop-specific climate and weather risk analysis. The analysis is focused on two main weather-related factors that play a fundamental role in agriculture: available soil water and temperature (FAO, 2019).

2.1. Weather data

Both weather-related variables are vital to crop growth but at the same time can potentially cause stress to the plant when above or below a certain, crop-specific value. Depending on the growth stage at which stress occurs and on stress duration, the harvest can be more or less severely affected. Particular focus is therefore put on estimating the following weather-related and crop-specific risks:

- Drought (available soil water falls below a certain level)
- Heat (temperature stays above a threshold for a prolonged period)
- Frost (temperature stays below a threshold for a prolonged period)

The weather data used in this work come from the meteoblue proprietary weather model NEMSGLOBAL (meteoblue AG, 2008). Based on the NMM (Nonhydrostatic Meso-Scale Modelling) technology, it provides hourly data, global coverage at a resolution of 30 km, 6 days forecast updated daily, and data availability since 1985. These unique characteristics make NEMSGLOBAL particularly suitable for global climate analysis. Alternatively, ERA5 re-analysis data or higher resolution NEMS data could be used where available. The medium range forecast data come from the meteoblue Learning Multimodel (meteoblue AG, 2016).

A large variety of seasonal forecasts is used, starting with the ECMWF daily seasonal forecast. Seasonal forecast uncertainty can be assessed by looking at further seasonal forecasts calculated from monthly anomaly data available from different publicly available weather models. Sources include European Centre for Medium Range Weather Forecast (ECMWF), Japan Meteorological Agency (JMA), UK MetOffice, MeteoFrance, Deutscher Wetterdienst (DWD), US National Center of Environmental Prediction (NOAA), and Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC). In addition, meteoblue provides an ensemble forecast based on the mean of all included monthly seasonal forecast models.

2.2. Drought events

For the scope of this work, drought events that lead to water stress for the plant occur when the available soil water falls below a threshold (“drought threshold”). The daily available soil water (ASW_d) is calculated using a single-layer soil water balance bucket model (Laio, 2001), simplified as follows:

$$WB_d = ASW_{d-1} + P_d - ET_d$$

$$ASW_d = \begin{cases} 0, & WB_d < 0 \\ WB_d, & 0 \leq WB_d \leq S \\ S, & WB_d > S \end{cases}$$

where:

- WB_d = simplified single-layer soil water balance
- ASW_{d-1} = available soil water at previous day
- P_d = daily precipitation (mm), from weather data
- ET_d = daily evapotranspiration (mm), from weather data
- S = soil capacity (mm)

$$Drought\ event:\ ASW_d \leq ASW_c$$

where:

- ASW_c = drought threshold (mm)

The initial value for daily available soil water is computed by running the model for the 60 days prior to the planting date. Tests have shown that periods > 60 days do not provide significantly different initial values. The drought threshold and the soil capacity default to values of 3 mm and 100 mm, respectively.

2.3. Frost and heat events

For the scope of this work, frost events are defined as the hourly temperatures falling below a frost threshold $T_{c,f}$ (default: 0°C) for longer than the critical event duration t_c (default: 3 hours).

$$Frost\ event:\ T \leq T_{c,f} \quad for \quad t > t_c$$

where:

- T = hourly temperature (°C), from NEMSGLOBAL weather model
- $T_{c,f}$ = frost threshold (°C)
- t = time (hours)
- t_c = critical event duration (hours)

Analogously, heat events are defined as the hourly temperatures raising above a heat threshold $T_{c,h}$ (default: 30°C) for longer than the critical event duration t_c (default: 3 hours):

$$Heat\ event:\ T \geq T_{c,h} \quad for \quad t > t_c$$

where:

- $T_{c,h}$ = heat threshold (°C)

Event thresholds and critical durations can differ depending on crop and location: they are therefore editable by the user according to better/local knowledge and the default values themselves may in future be improved (see Section 5).

2.4. Crop specific risk

Risk assessment is important for a huge variety of fields and applications; among those, farming risk management is an important, widely studied branch (Kahan, 2008).
A quantification of risk helps evaluating mitigation options and making decisions based on quantitative criteria.

Crop growth is directly related to growing degree days (GDD) (Prentice, et al., 1992), the accumulation of thermal energy over time. This accumulation varies from year to year, and the crop risk analysis here is therefore related to GDD and not to calendar days. For GDD calculation, the following formula is applied:

$$GDD = \sum_{d=d\_start}^{d\_end} \frac{(T_{d,max} + T_{d,min})}{2} > T_b$$

where:

- d_start = first day of growing season (planting day)
- d_end = last day of growing season
- $T_{d,max}$ = daily maximum temperature (°C), from NEMSGLOBAL weather model
- $T_{d,min}$ = daily minimum temperature (°C), from NEMSGLOBAL weather model
- T_b = crop base temperature (°C)

GDDs are the main growth stage driver: a crop's growth stages begin at values of GDD that are specific to crop and variety. The values we use as defaults are based on averages of values found in literature.

For each crop, each growth stage is associated with a weather event impact value that reflects how much a weather event affects a crop in each growth stage. This creates crop-specific "impact tables" that list crop phenological stages, the average GDD required to reach a stage, and the impact that drought, frost, and heat events have on the crop in each of its stages. An example is for spring barley is given in Table 1. A complete set of impact tables for supported crops is given in Appendix – Default parameters.

Table 1: Impact table for spring barley.

Growth stage	**Average GDD**	**Drought impact**	**Frost impact**	**Heat impact**
Emergence	127	0.3	0.7	0.8
Leafing	165	0.5	0.8	0.7
Tillering	334	0.7	0.8	0.6
Stem elongation	522	0.9	0.9	0.5
Anthesis	837	1	1	0.5
Seed fill	1036	0.9	0.8	0.5
Dough	1316	0.7	0.5	0.4
Maturity	1396	0.4	0.5	0.2
Harvest	1745	0.3	0.3	0.1

We follow the ISO quantification (ISO, 2018) of risk (R) by determining the combined probability of the likelihood of weather event to occur and the impact the event can have:

$$R = L * I$$

where:

L = Likelihood of a weather event to occur at a certain location at a certain growth stage
I = Impact the event has on a specific crop during a specific growth stage.

Figure 3 illustrates the likelihood and impact data used to calculate risk.

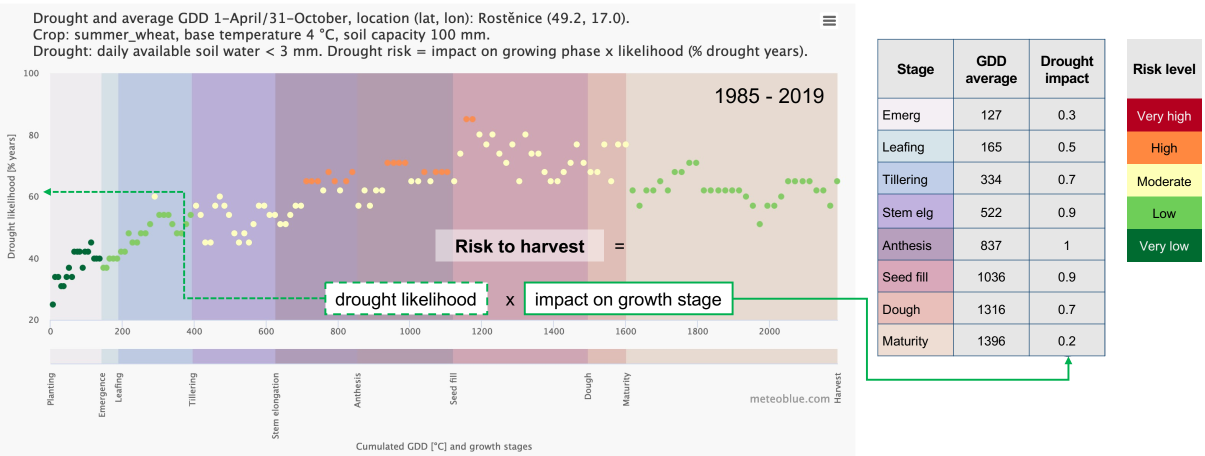

Figure 3: Growth-stage dependent risk calculation.

As before, default values are chosen by meteoblue according to available literature values and/or agronomical knowledge. They can be changed by users if better values are available.

3. Crop risk diagrams

The meteoblue crop risk diagrams combine climate, weather, and crop data to (1) assess local crop-specific climate risk based on weather event frequency in a suitably chosen reference period, and (2) indicate local crop-specific weather risk during a crop's growing season based on the medium range and seasonal weather forecast. All related information is presented concisely such that risk to crops can be quickly assessed, different locations, seasons, and crops can be easily compared, and options for action can be quickly evaluated.

3.1. Crop climate risk calculated from historic data

The crop climate risk analysis diagram (Figure 4) allows users to assess crop-specific climate risk in a particular location based on a reference period that can be chosen by the user. The horizontal axis of the diagram represents GDD, the vertical axis represents the likelihood of drought (top), frost (centre), or heat events (bottom) occurring. The vertical coloured strips represent growth stages of the crop; their boundaries are given by the relationship between GDD and a crop's growth stage (see Table 1). The width of each strip depends on the GDD value associated with its corresponding growth stage. At season start (the planting date), the GDD value is set to 0.

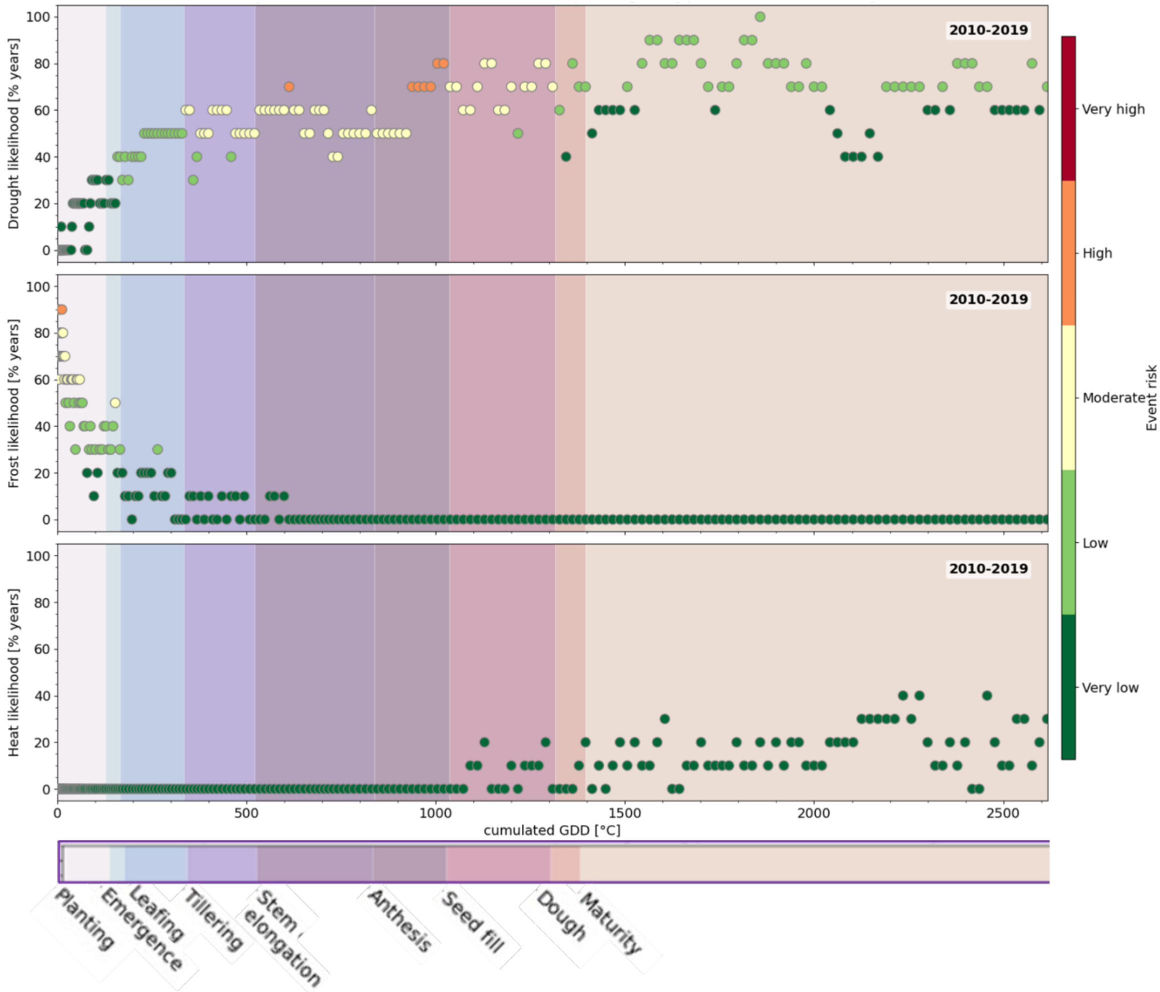

Figure 4: Example of crop climate risk diagram for spring barley, growing season February-August, reference period 2010-2019. Location (lat, lon) 49.1, 16.6; base temperature 4°C; soil water capacity for drought calculation 100 mm.

How much a weather event impacts a crop depends on the crop's growth stage, shown in Table 1 as well. Impact values are derived from literature and expressed as values between 0.0 and 1.0, with low values meaning low impact.

The vertical axis is the likelihood of the selected event (drought, frost, heat) occurring. The likelihood is based on historical statistics for the selected reference period. Testing suggests that a reference period of at least 5 years should be chosen to obtain a useful diagram.

Dot colours indicate the level of risk to the crop according to the colour scale on the right of Figure 6. The risk level is calculated as the product of likelihood of a drought, frost, or heat event occurring and its impact on the crop in its corresponding growth phase.

These diagrams, already exploited in farming case studies (Gobin, et al., 2020), aim to support strategic, long-term decisions by helping answer questions such as which crops to plant in response to changing climate conditions. They also help taking pre-planting operational decisions such as which crop variety to choose.

3.2. Crop weather risk monitoring and prediction

The crop weather risk prediction diagram (Figure 5) indicates the risk to a selected crop based on drought, heat, or frost in the current season at a selected location, based on a 7-day and a seasonal forecast. As with the crop risk analysis diagram, each growth stage has an associated impact of the respective weather event, expressed in the crop impact table (Table 1).

As with the crop climate risk analysis diagram, the horizontal axis shows cumulated growing degree days (GDD), starting with 0 °C GDD from a typical planting date for the selected crop. The planting date can be adjusted by the user for what-if analyses. The colour bar below the diagram indicates the selected crop's growth stages, analogous to the vertical colour strips in the background of the crop climate risk analysis diagram. The growth stage names (derived from phenologic development stages, (Wikipedia)) on the colour bar below the diagram are positioned at the end of each growth stage.

Depending on whether looking at drought, frost, or heat risk, the blue curve shows an estimate of available soil water, daily minimum temperature, or daily maximum temperature, respectively, based on the weather up to the current date. The magenta curve shows a 7-day forecast, and the tan curves show the various seasonal forecasts as described in Section 2.1.

The black and grey curves show the weather's (average) behaviour in reference periods that the user can change. In addition, the grey area covers two standard deviations of the past 35 years' mean value of the selected weather variable. Choosing, for example, one past year with a good harvest and one with a less good harvest as reference periods allows users to compare the current year with those. This provides valuable context in practice, as users tend to remember which interventions worked and which didn't in those years.

The vertical axis is the value of the weather variable that drives the selected event: available soil water for drought events, daily maximum temperature for heat events, and daily minimum temperature for frost events.

Background colours indicate level of risk and are derived as follows. Weather variable values are discretized in five classes, one above (or below) the event threshold value, and four below (or above) the event threshold value. Each class is associated with a likelihood value between 0.0 and 1.0 such that the likelihood value increases as the threshold is approached and is set to 1.0 once the event threshold value is passed. The level of risk due to drought, heat, or frost to the crop in its various growth stages is computed as the product of likelihood and impact as described in Section 2.4, represented graphically by the diagram's background colours. The admittedly simplistic model of likelihood ("the closer the weather variable value approaches the weather event threshold, the higher is the probability of the weather event occurring") allows us to (1) highlight when a weather variable passes a threshold value and (2) indicate the risk to a crop based on the impact of a weather event on the crop in certain growth phase.

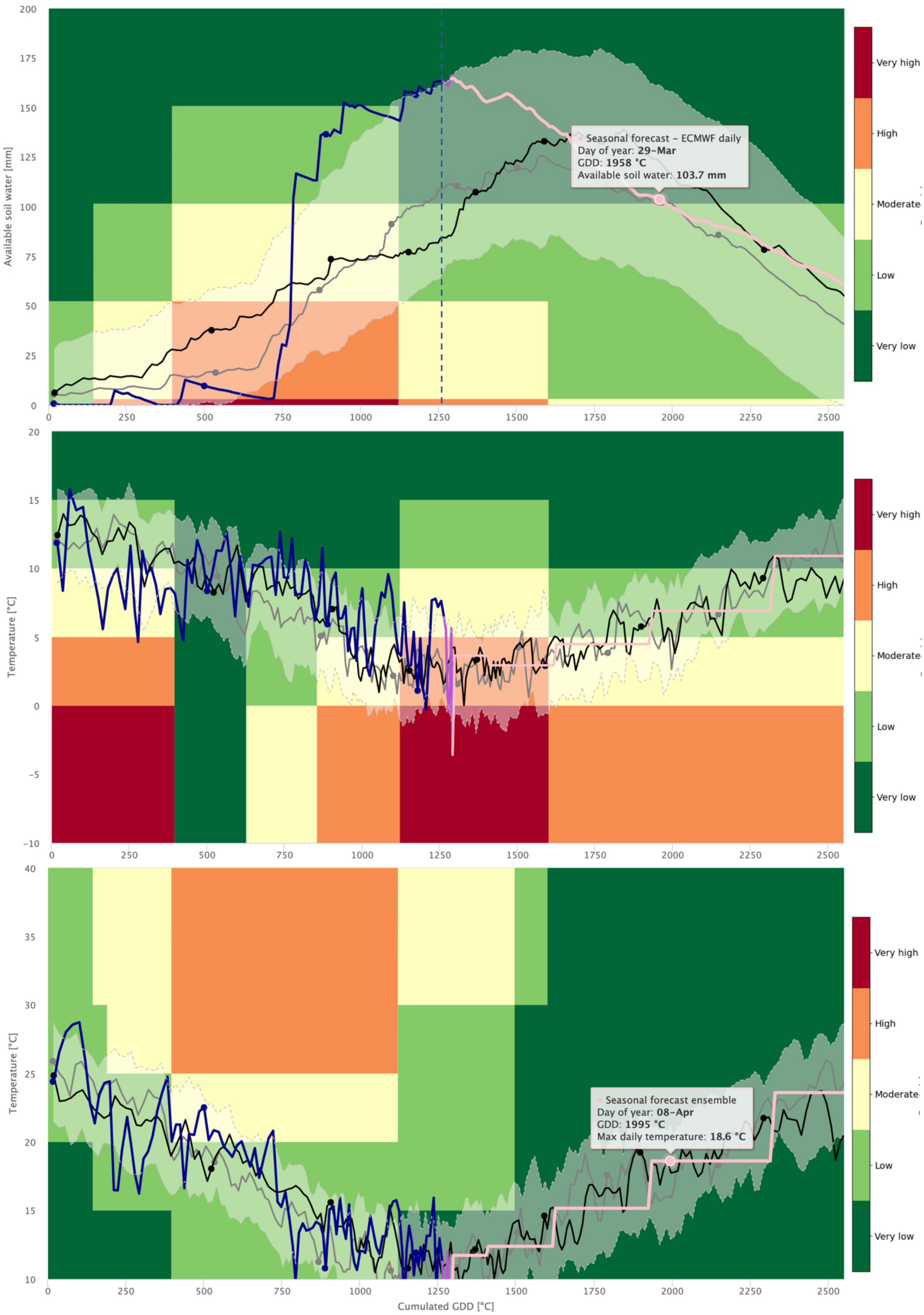

Figure 5: Example of crop weather risk monitoring and prediction diagram for drought risk (top), frost risk (centre) and heat bottom). Winter wheat, growing season October-May. Location (lat, lon): (40.0, 16.6). Base temperature 0°C. Soil capacity 200 mm. Water stress: available soil water < 3 mm. Frost: daily min temperature < 0°C. Heat: daily max temperature > 30°C. Dotted lines: climatic average 1985-2020 +- standard deviation.

These diagrams aim to support operational decisions pre- and post-planting.
Pre-planting decisions include to adjust the planting date, according to the 7-day and seasonal forecast, and to anticipate necessary interventions during the season.
Post-planting decisions include those required for weekly intervention planning.

4. Examples

The full potential of both crop climate risk analysis and crop weather risk monitoring and prediction diagrams lies in the possibility to compare two or more of them simultaneously. Some example applications and interpretation possibilities for mitigation and decision making are given below.

4.1. Climate change impact analysis

Figure 6 shows the comparison of two 10-year periods for a given crop at a given location. This gives quick insight into whether climatic conditions with an impact on the crop have changed, and by how much.

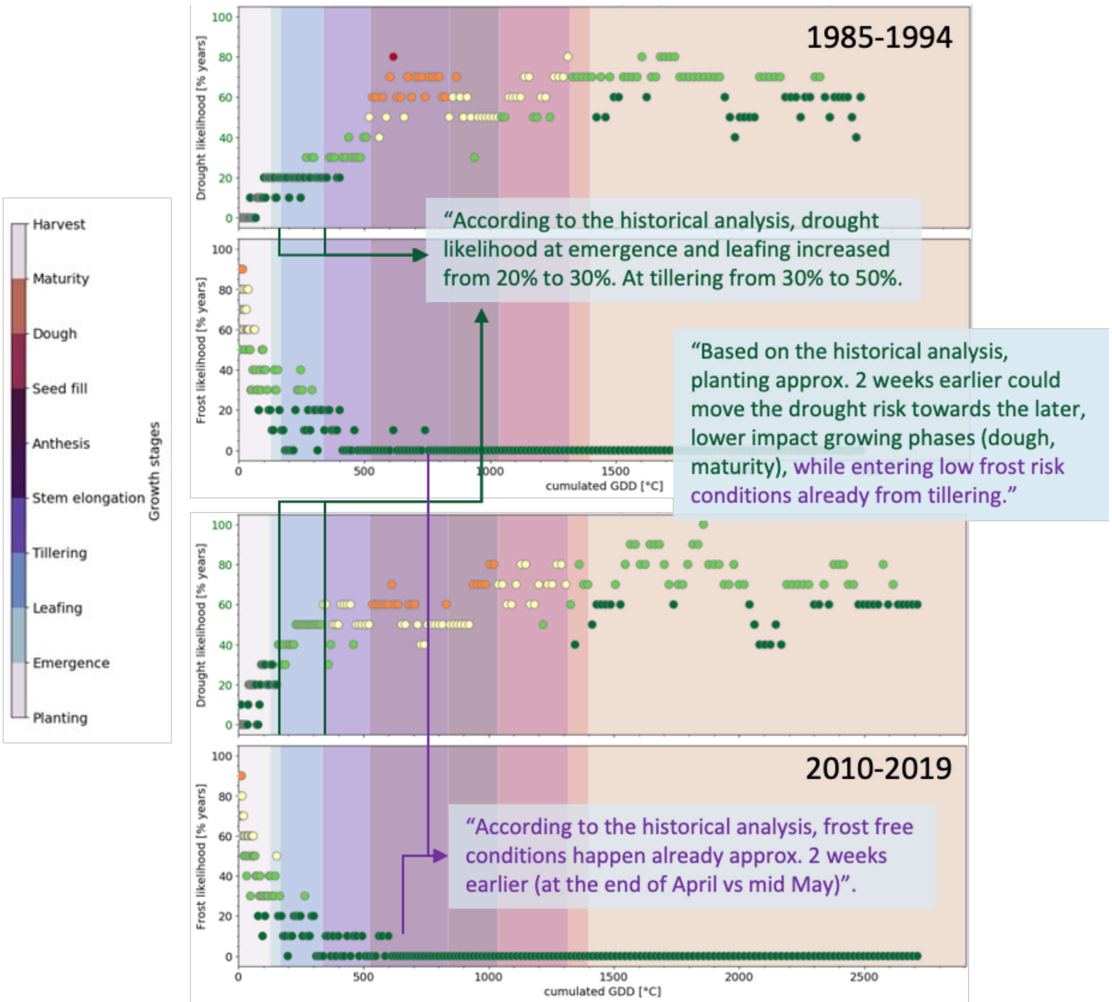

Figure 6: Crop climate risk comparison, time periods 1985-1994 vs 2010-2019. Crop: spring barley, location (lat, lon): (49.1, 16.6).

4.2. Long-term planning

Figure 7 shows the comparison of a set of crops at a set of locations in one reference period. One can see quickly that Parma and Bernburg are less suited for maize than Basel, and that Bernburg is less suited for spring barley than Basel and Parma.

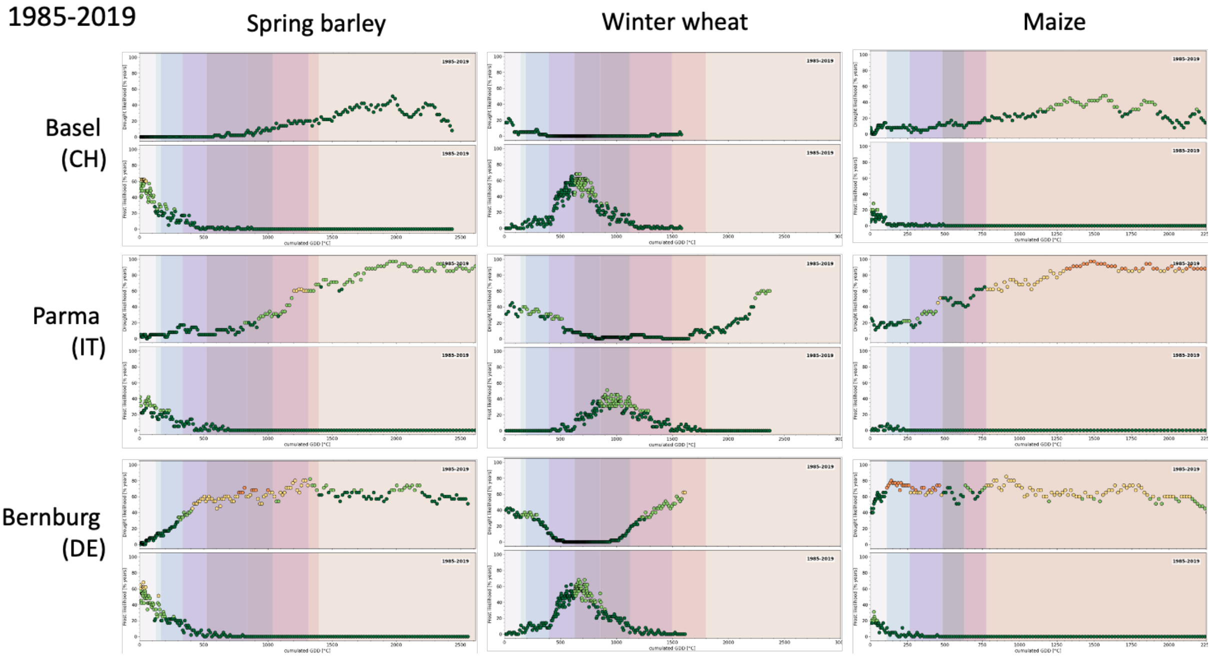

Figure 7: Crop climate risk comparison, time frame 1985-2019. Crops: spring barley, winter wheat, maize. Locations: Basel (CH), Parma (IT), Bernburg (DE). One can quickly spot that, for example, Bernburg and Parma are not suitable for maize unless irrigated.

Supported decisions include:

- which crop to choose for a specific location (e.g., "spring barley may incur in frost in the early growth stages in Basel, while winter wheat and maize do not present this criticality")
- when to plant a crop (e.g., "to grow spring barley in Bernburg, planting may be postponed to mid-February to avoid frost. This may cause a higher drought risk during flowering, so irrigation interventions should be accounted for")
- interventions to anticipate (e.g., "irrigation required in the early stages of the growing season, if planting maize in Bernburg")

4.3. In-season warnings

Figure 8 gives examples of in-season warnings that can be derived from the crop weather risk prediction diagram. Curves plotted from past periods serve as reference and help the viewer to quickly compare predicted weather to what they have experienced in the past.

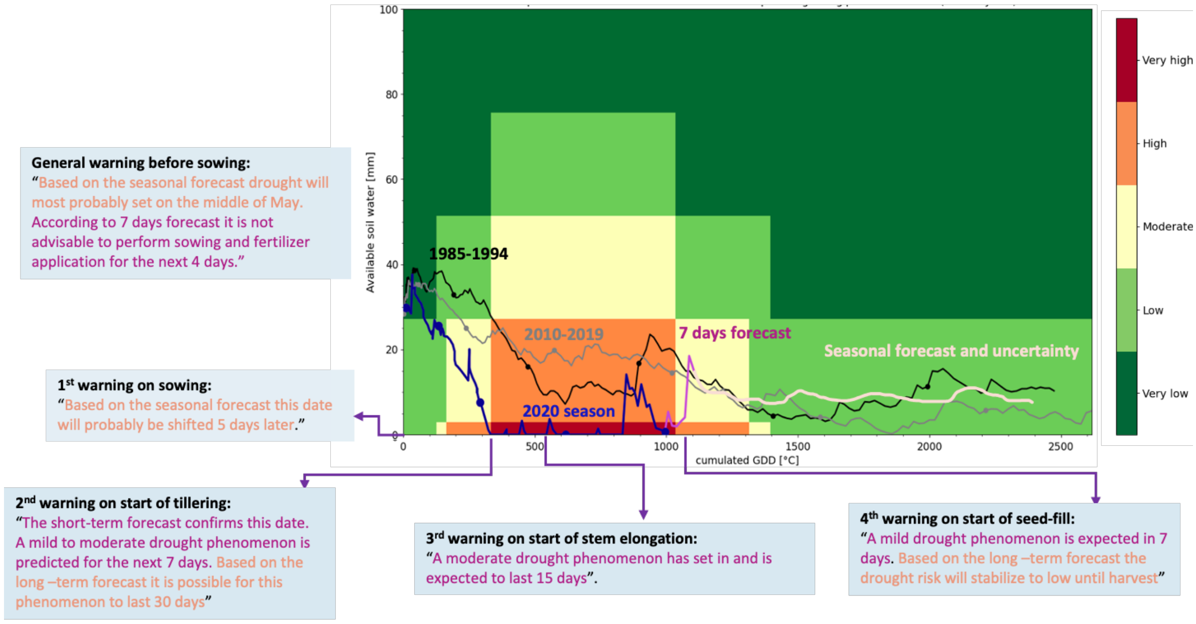

Figure 8: Crop weather risk monitoring and prediction. Crop: spring barley, location (lat, lon): (49.1, 16.6).

5. Supplying local data to improve accuracy of the crop risk diagrams

The crop risk analysis and crop weather risk prediction diagrams can be retrieved from meteoblue via calls to an API (application programming interface) implemented as web services. When calling the API, users can supply their own parameters for weather events and crops to tailor the analysis to their specific local conditions. The API call specification is not in scope for in this paper.

Weather event definition

The weather event definitions given in Section 2 can be replaced with other values if needed.

Crop information

As mentioned above, the default values for the crop parameters meteoblue uses in the impact tables are approximate values gleaned from literature. Users can supply impact tables with their own data to improve the local risk assessment.

Local soil information

If local soil information is available, the default values for soil water capacity and drought threshold for drought events can be changed. This allows users to express local soil characteristics in terms of soil water capacity and drought threshold.

6. Possible future improvements of accuracy

There are several possibilities to further improve the accuracy of the method.

More accurate soil water balance

The simplified water balance, based on the soil water balance bucket model, could be enriched with information such as root depth, soil type, soil layers.

Automatic integration of in-situ measurements

Measurements (e.g., temperature, precipitation, soil moisture from sensor data) would also be valuable to validate and locally adjust the model estimates.

Automatic integration of operational information
Fundamental to improve the accuracy of the model, would also be to integrate real-time field management and observation data (e.g., irrigation, growth stage).

Improved heuristics for providing default parameters
The default parameters, particularly the ones related to weather events (soil capacity, drought/frost/heat threshold, critical event durations) are strongly dependent on crop, soil characteristics and location: default parameters could therefore be dynamically generated based on the crop selected and soil type.
Analogously, the default season start (already crop-dependent) could be made also location (latitude) dependent.

Covering additional risks
Additional weather-related risks could be supported (e.g., tropical nights risk, icing risk, extreme precipitation risk).

Including climate prediction
Local climate predictions computed from RCP scenarios (Wikipedia) could be added, extending the range of periods that could be analysed and compared via crop risk analysis diagrams.

Interpretation aids
The crop risk diagrams are designed to support decision making. Providing descriptive interpretation aids could improve the utility of the diagrams and help users to quickly interpret the diagrams for the locations and crops they are interested in.

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Appendix – Default parameters

Default weather event parameters

The default parameters for weather events are listed below.

- **Drought event**
  - Threshold: daily soil water availability falls below 3 mm.
- **Frost event**
  - Frost threshold 0 °C
  - Duration > 3 hrs
- **Heat event**
  - Heat threshold 30 °C
  - Duration > 3 hrs

User defined values for those parameters can be supplied as API call parameters.

Default crops and parameters

Crops with pre-defined parameters are listed in Table 2. User defined values for those parameters can be supplied as API call parameters, or additional crops can be defined along with their parameters.

Table 2: Default crops and parameters. [(1)]For locations in the southern hemisphere season start and end dates are shifted by six months.

	Summer Wheat	Spring Barley	Winter Wheat	Winter Barley	Soy-beans	Maize	Potatoes	Sun-flower	Vineyard	Cotton
Season month_start [(1)]	4	2	10	10	4	4	4	4	4	2
Season month_end	10	8	5	7	10	10	9	10	10	8
Season day_start	1	1	1	1	1	1	1	1	1	1
GDD t_base	4	4	0	2	10	10	7	4	10	15
GDD t_max	37	35	25	33	30	35	27	36	35	40

Default impact tables

Default impact tables are shown in Table 3 to Table 9. User defined impact tables can be supplied as API call parameters.

Table 3: Impact table for summer wheat

Stage	GDD minimum	GDD maximum	GDD average	Drought impact	Frost impact	Heat impact
Emergence	125.0	160.0	143	0.3	0.9	0.7
Leafing	169.0	208.0	189	0.6	0.9	0.6
Tillering	369.0	421.0	395	0.7	0.8	0.5
Stem elongation	592.0	659.0	626	0.95	0.1	0.7
Anthesis	807.0	901.0	854	0.95	0.5	0.9
Seed fill	1068.0	1174.0	1121	0.9	0.7	0.8
Dough	1434.0	1556.0	1495	0.7	0.8	0.7
Maturity	1538.0	1665.0	1602	0.7	0.9	0.5
Harvest	n\a	n\a	1825	0.4	0.7	0.1

Table 4: Impact table for spring barley

Stage	GDD minimum	GDD maximum	GDD average	Drought impact	Frost impact	Heat impact
Emergence	109.0	145.0	127	0.3	0.7	0.8
Leafing	145.0	184.0	165	0.5	0.8	0.7
Tillering	308.0	360.0	334	0.7	0.8	0.6
Stem elongation	489.0	555.0	522	0.9	0.9	0.5
Anthesis	738.0	936.0	837	1.0	1.0	0.5
Seed fill	927.0	1145.0	1036	0.9	0.8	0.5
Dough	1193.0	1438.0	1316	0.7	0.5	0.4
Maturity	1269.0	1522.0	1396	0.4	0.5	0.2
Harvest	n\a	n\a	1745	0.3	0.3	0.1

Table 5: Impact table for winter wheat

Stage	GDD minimum	GDD maximum	GDD average	Drought impact	Frost impact	Heat impact
Emergence	125.0	160.0	143	0.3	0.9	0.5
Leafing	169.0	208.0	189	0.6	0.9	0.6
Tillering	369.0	421.0	395	0.7	0.8	0.7
Stem elongation	592.0	659.0	626	1.0	0.1	1.0
Anthesis	807.0	901.0	854	1.0	0.5	1.0
Seed fill	1068.0	1174.0	1121	0.9	0.7	1.0
Dough	1434.0	1556.0	1495	0.7	0.8	0.6
Maturity	n\a	n\a	1600	0.7	0.9	0.3
Harvest	n\a	n\a	1700	0.4	0.7	0.1

Table 6: Impact table for winter barley

Stage	GDD minimum	GDD maximum	GDD average	Drought impact	Frost impact	Heat impact
Emergence	n\a	n\a	50	0.8	0.1	0.9
Leafing	n\a	n\a	230	0.9	0.0	1.0
Tillering	n\a	n\a	334	0.9	0.0	1.0
Stem elongation	n\a	n\a	1850	0.5	0.2	0.9
Anthesis	n\a	n\a	2200	0.4	0.6	0.8
Seed fill	n\a	n\a	2340	0.3	0.7	0.7
Maturity	n\a	n\a	2570	0.2	0.8	0.7
Harvest	n\a	n\a	2750	0.1	0.8	0.7

Table 7: Impact table for soybeans

Stage	GDD minimum	GDD maximum	GDD average	Drought impact	Frost impact	Heat impact
Emergence	57.1	89.4	74	0.3	1.0	0.2
50% flowering	677.9	899.5	789	0.5	0.9	0.5
100% flowering	746.3	960.5	854	0.7	0.7	0.6
Pod formation	854.5	1125.0	990	1.0	0.5	0.4
Maturity	1453.8	1913.2	1684	0.9	0.3	0.2
Harvest	1694.0	2058.0	1876	0.5	0.1	0.1

Table 8: Impact table for maize

Stage	GDD minimum	GDD maximum	GDD average	Drought impact	Frost impact	Heat impact
Emergence	n\a	n\a	111	0.3	1.0	0.7
6 collars	n\a	n\a	264	0.9	0.9	0.8
12 collars	n\a	n\a	483	0.9	0.9	0.9
Last tassel	n\a	n\a	630	0.2	0.9	0.8
Silking	n\a	n\a	778	0.3	0.7	0.6
Harvest	n\a	n\a	1500	0.7	0.7	0.2

Table 9: Impact table for potato

Stage	GDD minimum	GDD maximum	GDD average	Drought impact	Frost impact	Heat impact
Emergence	150.0	200.0	175	0.3	0.7	0.9
Flowering	n\a	n\a	700	1.0	1.0	0.8
Maturity	n\a	n\a	1350	0.5	0.4	0.7
Harvest	n\a	n\a	1745	0.3	0.2	0.6

Table 10: Impact table for sunflower

Stage	GDD minimum	GDD maximum	GDD average	Drought impact	Frost impact	Heat impact
Emergence	109.7	128.8	120	0.5	0.1	0.9
Bud visible	571.6	640.8	607	0.7	0.5	0.9
Immature bud	869.1	1044.8	957	0.8	0.6	0.8
First flowering	1044.8	1335.6	1191	1.0	0.7	0.7
50% flowering	1158.9	1397.3	1279	0.9	0.8	0.6
Last flowering	1357.3	1677.2	1518	0.9	0.9	0.5
Maturity	2187.0	2292.2	2240	0.6	0.7	0.3
Harvest	n\a	n\a	2310	0.2	0.3	0.2

Table 11: Impact table for vineyards

Stage	GDD minimum	GDD maximum	GDD average	Drought impact	Frost impact	Heat impact
Bud break	40	75	58	1.0	1.0	0.8
Flowering	333	409	371	1.0	0.8	0.7
Veraison	965	1181	1073	0.7	0.6	0.6
Maturity	1251	1940	1596	0.5	0.8	0.5
Harvest	1390	2220	1805	0.2	1.0	0.4

Table 12: Impact table for cotton

Stage	GDD minimum	GDD maximum	GDD average	Drought impact	Frost impact	Heat impact
Emergence	27	34	31	0.2	1.0	0.1
Flowering	166	195	181	0.8	0.9	0.3
First square	236	264	250	0.8	0.9	0.4
First flower	430	472	451	0.8	0.8	0.4
Open boll	472	528	500	0.3	0.7	0.2
Harvest	1222	1445	1334	0.1	0.5	0.1

