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Evaluating Climate Suitability for Agriculture in Switzerland

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Abstract: With climate change increased water shortage and extreme weather events during the cropping season may cause more frequent crop loss, yield instability, and make cultivated areas less suitable for traditional crops. In order to develop long-term agricultural policies, planners need to understand the likely impacts of climate change on the climate suitability for different cultivation types. Agroclimatic indices have great potential to communicate the impacts of climate change. However, each metric only represents a specific aspect of the climate that may or may not be relevant for the growth of a certain crop type. To guide planners and policy makers, different indices have to be aggregated in a comprehensible manner. In this paper we present a framework for estimating agricultural suitability for major crops in Switzerland. The framework is based on an evaluation of agroclimatic indices for relevant phenological phases of a range of crops. This allows for taking into account that climate change may lead to significant shifts in growth phases and sensitive periods. Suitability functions are defined for each index. A weighted linear combination is used to aggregate the different elements of climate suitability for each crop and cultivation type. Suitability functions and weights are derived from scientific literature and expert knowledge.

***Keywords**:* Climate indices; agriculture; suitability evaluation; climate change

1. INTRODUCTION

Climate plays a fundamental role in agriculture. The quantity and quality of yields can be affected by water stress, heat stress or frost or by pests and diseases [Kassam et al. 1991]. European agriculture may be especially susceptible to meteorological hazards because it is based on highly developed farming techniques [Alexandrov et al. 2008].
In recent decades shifts in plant phenology have been observed, showing that ecosystems are already responding to global environmental change: earlier flowering and extended periods of active plant growth across much of the northern hemisphere have been interpreted as responses to warming [Studer et al. 2007]. However, at the same time plants grow faster, leading to decreases in quality and quantity of yields [Orlandini et al. 2009]. Such changes lead to shifts in the geographical distribution of climate suitabilities for different crops. Planners and land managers need to understand these changes for strategic resource and development planning and in order to develop long-term adaptation strategies [Salinger et al. 2000].

Agroclimatic or agrometeorological indices have great potential to quantify and communicate the impacts of climate change on agriculture [Bootsma et al. 2005, Patra and Sahu 2007, Orlandini et al. 2009, Eitzinger et al. 2009]. They can be used to describe the effects of climatic conditions on key agricultural aspects, including production, protection, fertilization, site selection, irrigation, etc. [Alexandrov et al. 2008]. Therefore, agroclimatic indices can be very helpful for farmers in their decisions about crop management options and related farm technologies [Eitzinger et al. 2009].

However, each index only represents a specific aspect of the climate that may or may not be relevant for the growth of a certain crop type. To guide land managers and planners, different indices have to be aggregated in a comprehensible manner. Thereby, possible interactions between different climate indices need to be taken into account. For example, a certain number of growing degree days may only be suitable for the growth of a specific crop if the precipitation sum is also within a suitable range. Such interactions can not easily be represented using empirical modeling approaches such as in Hundal et al. [2003].

In this paper we present a framework for an aggregated evaluation of agricultural suitability for major crops in Switzerland. The framework is based on agroclimatic indices that are calculated for relevant phenological phases of a range of crops. This allows for taking into account that climate change may lead to significant shifts in growth phases and sensitive periods. Suitability functions are defined for each index. A weighted linear combination is used to aggregate the different elements of climate suitability for each crop and cultivation type. Suitability functions and weights are derived from scientific literature and expert knowledge.

2. METHOD

2.1 Evaluation concept

A quantitative approach is developed to facilitate the crop-specific climate suitability evaluation. The evaluation involves six steps, which are explained in the following.

Step 1: Determination of growing degree days for relevant phenological phases
Crop phenological development is expressed as a function of growing degree days. To represent the various stages of development, growing degree day thresholds have to be identified for each phase and crop. This enables the dynamic determination of phenophase-specific climate sensitivities. For example, winter wheat is assumed to be more sensitive to water stress during flowering than grain filling. Depending on the climate, the phenological development might differ from year to year and thus also the relevance of precipitation deficits at individual days of the year could differ.

Step 2: Selection of relevant climatic indices
To quantify phenophase-specific climatic influences on crops, different climatic indices can be selected. Indices of drought, excess rain, frost and, to a minor degree, heat stress are probably among the most relevant in Europe [Eitzinger et al. 2009]. For this classification approach, the interpretation of indices has to be intuitive as the evaluation is based on expert knowledge.
Frost and heat stress can be quantified through relatively simple indices such as number of frost days (days with T_{min} < 0°C) or number of heat days (days with T_{max} > 35°C). Excess rain can be quantified in relation to precipitation percentiles or as daily rainfall exceeding a crop specific threshold. Drought indices have to quantify the lack of water during plant growth. Thus, they have to take account of the physical and biological properties of the particular crop in order to reflect its sensitivity towards water stress [Eitzinger et al. 2009]. A large variety of drought indices is available from the literature (e.g. the Standardized Precipitation Index (SPI), the ratio of actual to potential evapotranspiration (ET/ETP), the Palmer Drought Severity Index (PDSI)). In addition to these climate indices also the length of different phenological phases can be relevant for the quantity and quality of yields, as crops that mature faster accumulate less biomass.

Step 3: Determination of index-specific suitability ranges and weightings
Once the relevant climatic indices have been identified for the selected phenophases, both index-specific suitabilities s_i and weights w_i need to be specified. s_i-values are assumed to range from 0 to 1, with 0 indicating no suitability and 1 indicating optimum suitability of an index value. Weights w_i are assigned to the indices according to their importance for the crop development and so that they add up to 1. In Fig. 1 for instance, water and heat stress indices are equally weighted and weighted higher than the index characterising the rate of

development. Weights and index-specific suitabilities are initially assigned based on a literature review and will be refined in future work based on expert evaluations.

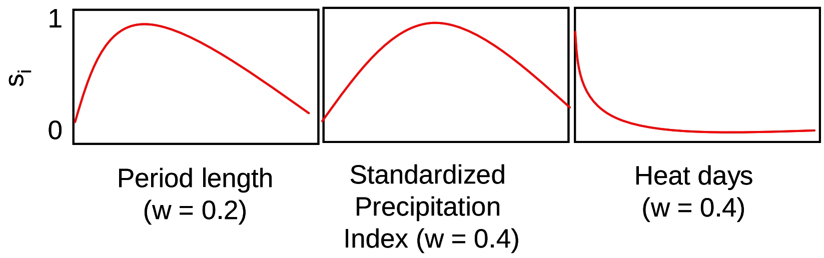

Figure 1. Example of index-specific suitability s_i functions and weights w_i assigned to three different climatic indices.

The expert-based evaluation of weightings for a large range of agroclimatic indices is often too complex to be made off the top of one's head. A structured approach is required to facilitate the weight assignment and allow for an aggregated assessment of climate suitability. The Analytic Hierarchy Process [AHP, Saaty 1980] provides a means for dealing with such complex multi-criteria decision problems. It has also been applied successfully for multi-criteria evaluation of land suitability [Hood et al. 2006, Perveen et al. 2008, Thapa and Murayama 2008, Rahman and Saha 2008, Cengiz and Akbulak 2009, Tienwong et al. 2009]. Within the AHP, the evaluation is broken down into the variables determining suitability, which are then arranged in a hierarchical order (Figure 2). Variable weights are determined based on pair-wise comparisons by experts. Thus, AHP provides a framework that allows hierarchical combination of criteria and incorporates expert participation in the evaluation process.

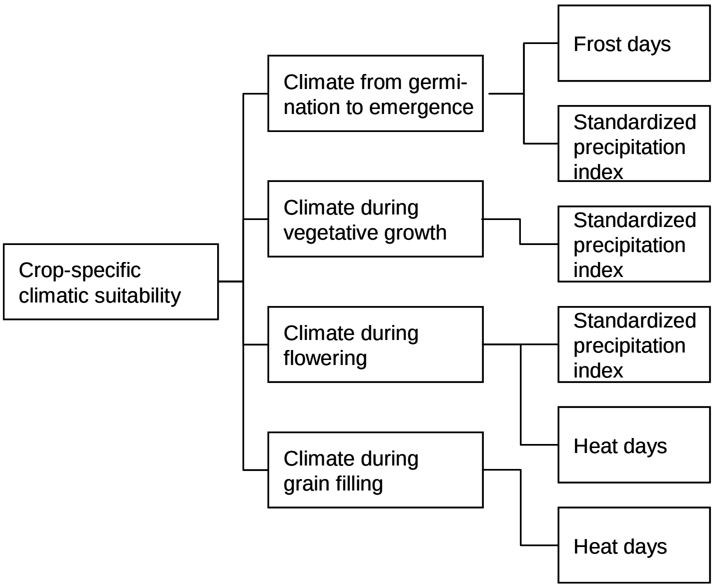

Figure 2. Example of hierarchical evaluation of crop-specific climate suitability.

Step 4: Definition of evaluation functions

To evaluate crop-specific climate suitability S_c based on the phenophase-specific climatic indices, a weighted average can be derived from the index-specific suitability values s_i. However, in some cases the linear combination of indices based on weightings as shown in Fig. 1 might not be appropriate due to interactive effects between the influencing variables. For example, Bowen and Hollinger [2004] assumed that precipitation, growing days, and winter minimum temperature follow the "law of the minimum". This means if a variable is limiting, the species can not be grown, even if all the other variables are not limiting. To take such dependencies into account evaluation rules can be introduced in the evaluation function.

Step 5: Spatial evaluation

The evaluation function defined in step 4 will at first be applied at the local scale, on the basis of routine observations carried out at a number of stations by the Swiss Meteorological Service (Figure 3). Thus, crop-specific climate suitabilities S_c will be derived for every location and year. Based on the local time series of climate suitabilities, averages and standard deviations of climate suitabilities can be derived. Average climate suitabilities would give an indication on the average potential yields, while the variability of climate suitability could give an indication on climate-related production risks.

The local values will be interpolated to produce crop-specific maps both of average climate suitabilities and variabilities of climate suitabilities.

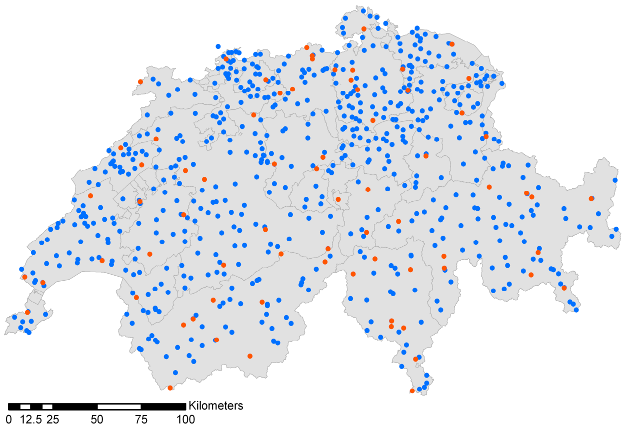

Figure 3. Locations of climate stations in Switzerland (red = all climate data automatically recorded, blue = only precipitation data recorded).

Step 6: Climate suitability classification

Finally, the averaged continuous climate suitability values will be discretized according to the FAO classification [FAO 1976], which is commonly applied for land evaluation (e.g. Triantafilis et al. 2001). Thereby, three suitability classes are distinguished: S1 = Highly suitable with no or non-significant limitations, S2 = Moderately suitable with intermediate limitations, and S3 = Marginally suitable with severe limitations. Non-suitable classes are subdivided in N1 = currently not suitable, and N2 = permanently not suitable. Suitability subclasses reflect different kinds of limitations (e.g. c = temperature regime, m = moisture availability). Class boundaries will be determined based on expert knowledge. Similarly, the variability values can be classified into different risk categories.

The evaluations will be integrated in a GIS to enhance the compatibility with other spatial data and allow for spatial analyses.

3. PRELIMINARY INVESTIGATIONS

Preliminary investigations on the phenology of maize were conducted based on growing degree day estimates by Lang and Müller [1999]. Figure 4 shows the dates of maize emergence, heading and maturity at the climate station of Magadino in Southern Switzerland at Lago Maggiore from 1980 to 2009. The same sowing date was assumed for all years (1^{st} of May). The figure shows that phenological stages can vary significantly between years depending on the temperature conditions. Also, there seems to be a slight shift towards earlier maturity dates from 1980 to 2009.

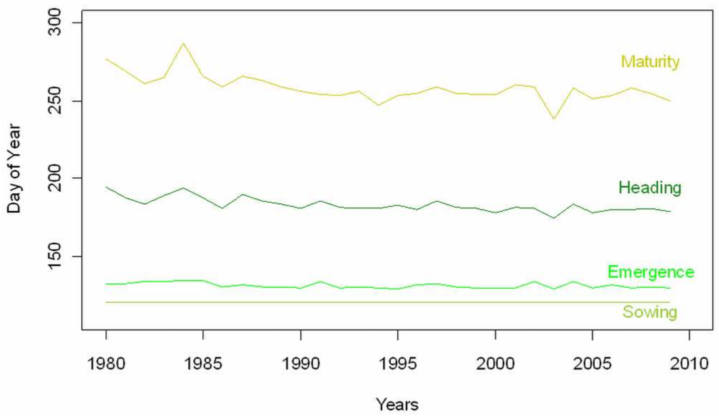

Figure 4. Phenological phases on maize simulated for the climate station of Magadino from 1980 to 2009 (Long 8°56', Lat 46°10', 203 m a.s.l.).

With climate change the phenological development is likely to be accelerated further due to increased temperatures. Figure 5 shows the simulated phenological stages for maize under current climatic conditions at Magadino (Figure 5a) compared to phenological stages estimated for a 2-degree increase in temperature (Figure 5b). With a 2-degree temperature increase maturity dates are estimated to be on average 15 days earlier.

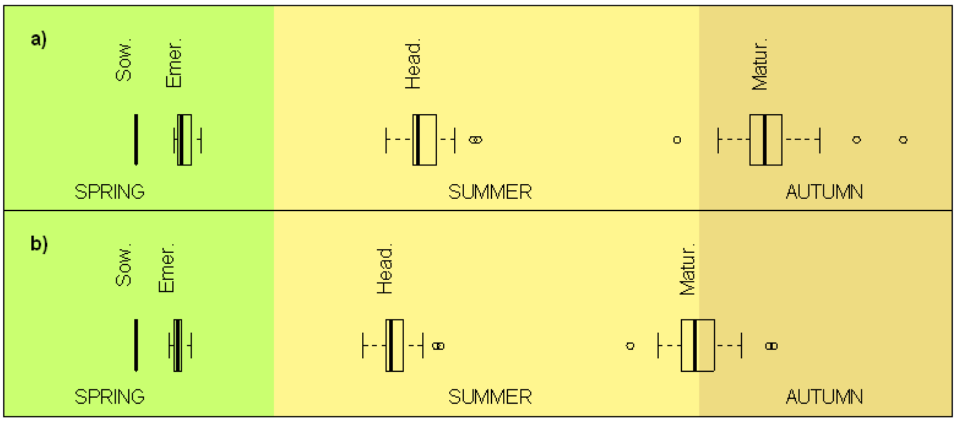

Figure 5. Phenological stages for maize simulated based on reference conditions (1980-2009, (a)) and with a temperature increase of 2°C (b) for Magadino (boxplots indicate inter-annual variability of phenological stages).

As temperature requirements and sensitivities to water stress vary depending on the phenological stage, the shifts in phenological development imply shifts in the climate sensitivities of crops. Figure 6 shows the distributions of maximum daily temperatures between heading and maturity of maize for different scenarios of climate and phenological development.

Maximum daily temperature between heading and maturity can be considered as a possible phenophase-specific climate index related to temperature conditions for growth. As shown in Figure 6 the climate index value can vary significantly depending not only on the climate conditions, but also on the definition of the phenological period. If the phenology shift would not be considered for evaluating the T+2 scenario, the climate index value would be strongly underestimated.

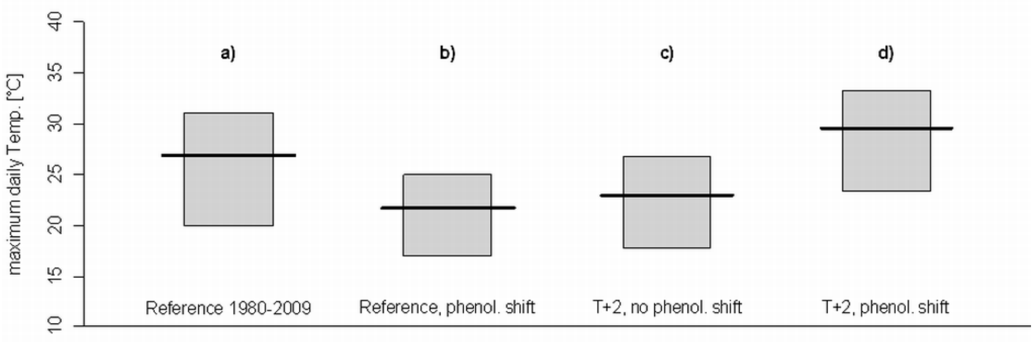

Figure 6. Distributions of average daily temperatures between heading and maturity of maize in Magadino for four scenarios: a) reference climate 1980-2009 and associated phenology, b) reference climate and phenological shift according to 2°C-temperature increase (T+2), c) T+2 climate and reference phenology, d) T+2 climate and associated phenology (black bars indicate median values, grey boxes enclosing 5th to 95th percentile).

The estimated increase in maximum daily temperatures between heading and maturity is likely to increase climate suitability for maize as the optimum temperature range for maize growth is between 25 and 35°C [Lang and Müller 1999]. However, for the overall evaluation of climate suitability for maize it will also be important to evaluate drought conditions as maize requires a relatively continuous supply of water. A serious drought effect may inhibit the positive effect of temperatures on maize suitability. Furthermore, minimum temperatures would have to be taken into account for an overall evaluation of climate suitability to quantify growth limitations and frost damages.

4. CONCLUSIONS AND OUTLOOK

The presented framework allows for a flexible evaluation of crop-specific climate suitability. The evaluation function can easily be modified or updated to integrate new information or to test assumptions. The GIS integration will enhance the user-friendliness of the derived climate suitability maps as it allows for the integration with other GIS data and for conducting spatial analyses.
The integration of phenophase-specific climate indices allows for a dynamic evaluation of climate suitability. Thus, also the impacts of climate change can be investigated. Furthermore, the consideration of variabilities in climate suitability allows for assessing production risks.
The approach will be implemented for evaluating climate suitabilities for the most important cultivation types in Switzerland (e.g. winter cereals, maize, pasture, vegetables, grapes, fruit). Based on these crop-specific evaluations an overall climate suitability map for agriculture in Switzerland will be derived indicating areas of optimum cultivation type. In the long term, the approach could be extended to incorporate a soil suitability assessment in addition to the climate suitability assessment. This could provide an even more comprehensive basis for land resource planning.

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