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Analyzing climate effects on agriculture in time and space

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Abstract

Climate in its spatial and temporal variability is one of the major drivers determining agricultural productivity in a region. In order to develop long-term agricultural policies, planners need to understand the likely impacts of climate change on agricultural suitability zones. In this paper we present a flexible approach for the spatio-temporal evaluation and analysis of climate suitability for different crops. First results of a case study application, aiming at investigating how climate suitability for grain maize production in Switzerland varies in time and space and may shift with climate change, are discussed.

Keywords: climate suitability; multi-criteria evaluation; climate indices; climate change; agriculture

1. Introduction

Climate plays a key role in agriculture. It defines productivity potentials [1] but also yield gaps and quality through water and heat stress, frost, or by pests and diseases [2]. It is therefore a major determinant of regional suitability for agricultural production. Short-term extremes in precipitation and temperature can be critical for crop growth, especially if they coincide with key stages of development [3]. European agriculture may be especially susceptible to meteorological hazards because it relies on highly developed farming techniques [4].

As climate conditions vary in time and space, so do climatic suitabilities for crop growth. Over the last decades, spatial shifts northwards and into central Europe have been estimated for warmer season crops like grain maize and grapevine [5, 6]. However, in areas where certain varieties of crops are grown near the limits of maximum temperature tolerance, heat spells can be particularly detrimental [7].

Planners and land managers need to understand these changes in climatic suitabilities in time and space for strategic resource and development planning and in order to develop adaptation strategies [8].

In this paper we present a flexible and comprehensive, rule-based approach for evaluating climate suitability for various crops. The approach is primarily based on expert knowledge, but can also incorporate data, which increases the objectivity of the model. Furthermore, the dynamics of crop phenological development is explicitly taken into account. Hence, effects of climate induced shifts in phenological developments can easily be assessed. The approach is being developed into user-friendly GIS tool. We show how it can be applied for assessing spatial and temporal trends in crop-specific climate suitabilities and for evaluating possible impacts of climate change.

2. The climate suitability evaluation approach

The crop-specific evaluation approach is based on agro-climatic indices that are calculated on an annual basis for relevant phenological phases. These phenophase-specific climate indices are called factors. Factor suitability

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functions are specified to relate factor values to factor suitability scores ranging from 0 to 1. The factor suitability functions can be defined based on scientific literature, expert knowledge, and empirical data. Different rules can be used to aggregate the elements of climate suitability for each crop and cultivation type and to derive a crop-specific climate suitability evaluation. The crop-specific evaluation of climate suitability comprises five steps, which are described in detail in the following and illustrated on the example of grain maize.

2.1. Determination of growing degree days for relevant phenological phases

To dynamically determine phenophase-specific climate sensitivities, crop phenological development is expressed as a function of growing degree days (GDDs), with GDD sum thresholds defining the transition from one phenological stage to the next.

For our test implementation for maize, approximate dates of maize phenology were provided by crop experts. The base temperature was set to 6°C in accordance with [9]. Based on this information and temperature data from major maize cropping regions, GDDs could be derived for the most important phenological stages: Emergence (100), begin of flowering (800), begin of grain filling (1100) and maturity (1600). The sowing date (May, 10th) was kept fixed and a maximum harvest date (October, 1st) was introduced to avoid unrealistic maturity periods.

2.2. Selection and calculation of climate indices

To quantify phenophase-specific climatic influences on crop development, different climatic indices can be selected. To allow for the indices to be easily interpretable by experts, we chose five very basic indices in our example:

- Average solar radiation [MJ/m^2]
- Average minimum temperature [°C]
- Average maximum temperature [°C]
- Water deficit (= reference evapotraspiration - precipitation) [mm]
- Phase length [days]

These five indices were found to be correlated with observed maize yields in previous investigations. Further indices such as number of heat days or frost days may have additional effects on maize growth and yields and could be integrated at a later stage.

2.3. Determination of factor suitabilities

Phenophase-specific climate indices are considered as factors. For each factor, factor suitability functions are determined to relate factor values to suitability scores. In our implementation for grain maize, the determination of factor suitabilities was steered by a comparison between observed yields and factor values. Observed yields were derived from the Farm Accountancy Data Network of Switzerland [10] as average yields in a 10-km radius around the respective climate stations providing the data for the evaluation of the factor values. Assuming that each climate index can have a limiting effect on crop growth, factor suitability functions were defined as envelope curves around the maxima of observed yields over the range of factor values.

2.4. Definition of evaluation function

Different rule sets can be defined to evaluate crop-specific climate suitability based on the previously determined factor suitability scores. For maize, we assume that climate effects are limiting within each phase, but growth in one phase can be compensated for by growth in another phase. Therefore, we chose to evaluate climate suitability for maize S as a weighted linear combination of the four phase-specific minimum suitabilities:

$$S = w_1 * min(s_{1,1}, \ldots s_{1,5}) + \ \ldots \ + w_4 * min(s_{4,1}, \ldots s_{4,5})$$

In this evaluation function the weights w_1-w_4 represent the relative importance of the five climate factors *s* in each of the four phenological phases. For this first implementation, the weights were derived using non-linear least-square regression based on the observed yield data ($w_1 = 0.39$; $w_2 = 0.17$; $w_3 = 0.21$; $w_4 = 0.18$). Based on this evaluation function, we could achieve a strong, highly significant correlation between estimated maize suitabilities and observed yields (Spearman rank correlation coefficient = 0.62).

2.5. Spatial evaluation

To arrive at a spatial representation of the climate suitability for grain maize, the evaluation function was applied for all stations and years for which the required climate data were available over a minimum of 13 years. Spatial distributions of estimated mean maize suitabilities and their coefficients of variance were represented in a map. Temporal trends in maize suitabilities were analyzed using the Mann-Kendall's trend test and the spatial distribution of trends was also visualized in a map.

3. Results

The map in figure 1a shows the spatial distributions of maize suitability scores at climate stations below 1500 m a.s.l. estimated for the period 1981-2009. To be able to display both the long-term average suitability as well as its inter-annual coefficients of variation, which may give an indication on production risk, symbol colors were chosen according to the mean score, while the symbol size was set in inverse proportions to the coefficients of variation (larger sizes representing lower variability). Figure 1b shows a map of the distribution of Mann-Kendall's tau values, which indicate the direction and strength of trends in maize suitabilities. Here, the symbol size was set to represent the significance levels of the respective tau values.

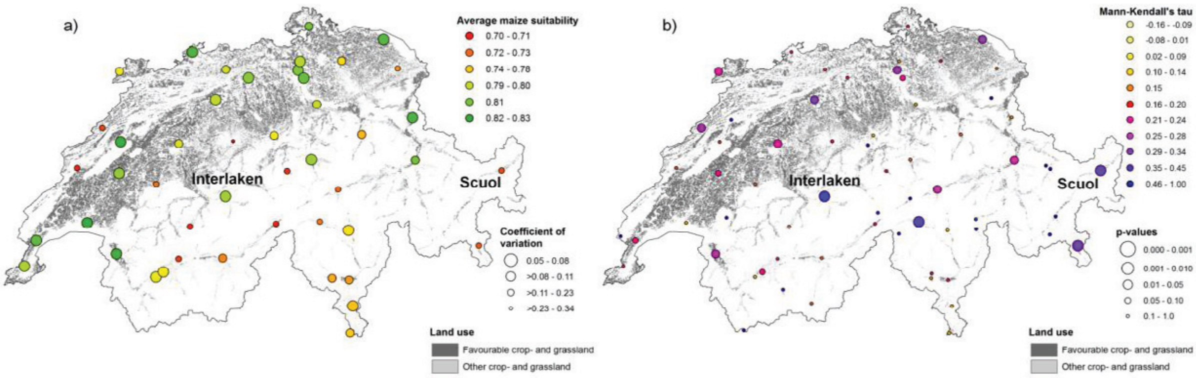

Figure 1: (a) Map of estimated maize suitability over the period 1981-2009. Colors show the average suitability scores and symbol sizes show coefficients of variation. Shown in grey in the background is the agricultural land use in Switzerland; (b) Trends in climate suitabilities for grain maize over the period 1981-2009 and agricultural land use in Switzerland.

According to figure 1a, estimated climate suitability scores for maize are greatest on the Swiss Plateau, between the Jura mountains in the north-west and the Swiss Alps in the south-east. These regions are also the main agricultural areas according to the Swiss land use map [11]. Unsurprisingly, under current conditions climate suitability for maize at higher altitudes –as in the Jura and especially in the Alps – is much lower. The climate suitability for maize is usually temperature-limited at these locations.

The Mann-Kendall trend tests reveal mostly positive trends in yield suitabilities over the period 1981-2009 (Fig. 1b). The few negative trends that were identified are not significant, whereas the most significant positive trends are found across the inner-Alpine domain at altitudes between 577 (Interlaken) and 1303 m a.s.l. (Scuol). At these stations, current climate suitability scores for maize are generally low , but the positive trends suggest improved suitability due to an increase in temperature affecting mainly the maturation period.

4. Discussion

Preliminary results of the first implementation of our approach for evaluating climate suitability for grain maize production are promising. The obtained spatial distribution of climate suitability scores is consistent with the agricultural land use pattern, and estimated shifts in climate suitability with climate change are in line with previous findings [12, 13, 3]. This indicates that climate suitability for current varieties of maize is increasing in the north and decreasing in the south. Our results also suggest that regions at higher altitudes that are currently not suitable due to temperature limitations, have become increasingly suitable over the last decades –a trend that may continue with climate change as long as temperature optima are not exceeded.

Uncertainties regarding assumed sowing dates, phenology dates, factor suitabilities, evaluation functions and climate projections were not addressed in this paper and require further investigation in order to increase the reliability of our approach and its application to the assessment of the projected impacts of climate change. In our example, the definition of factor suitabilities was mostly geared to the distribution of data. This could lead to problems often described for statistical crop models (i.e. collinearities between climate indices, limited range of observed climate values, uncertainties in observed yield data). A validation by crops experts, in particular of the evaluation functions, is therefore indispensable.

With respect to the crop phenology model, uncertainties may exist as sowing dates can differ regionally, leading to regional differences in phenological developments. As temperatures increase with climate change, earlier sowing dates may become an obvious adaptation measure, which would inevitably have implications for the phenological development. Furthermore, crop varieties can differ regionally and it is also likely that breeding of future varieties will account for environmental changes [14, 15, 16]. Our approach allows for taking such differences into account.

5. Conclusions and outlook

One great strength of the approach in general is its comprehensibility. The method is based on translating simple climate indices into crop-specific suitability scores using factor suitability functions, aggregation rules and weights that are explicitly related to physiological processes. This makes the evaluation function extremely transparent for the user. The possibility to utilize data as well as expert knowledge for deriving factor suitability functions and weights allows for introducing greater objectivity in the expert-based evaluation function. In the further development, the user-friendliness will be improved further by integrating the evaluation approach into a GIS. A prototype GIS tool is currently being implemented using Python in ArcGIS.

As the approach is very flexible, it offers diverse possibilities for applications, e.g. for the regional assessment of crop-specific climate suitabilities as shown in this study, and for testing impacts of climate change scenarios. Furthermore, it could be applied to analyze regional limitations for specific crops. Such information may be helpful for planning land improvements such as irrigation projects. Another possible application field is to test how modifications of the crop characteristics introduced through crop breeding or genetic engineering would affect the spatial distribution of climate suitabilities. This could help to inform breeding programs by identifying crop properties that would allow the crops to be grown in larger areas or that would adapt them to changing climatic conditions.

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