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Broadening the scope for ecoclimatic indicators to assess crop climate suitability according to ecophysiological, technical and quality criteria

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ABSTRACT

The cultivation of crops in a given area is highly dependent of climatic conditions. Assessment of how the climate is favorable is highly useful for planners, land managers, farmers and plant breeders who can propose and apply adaptation strategies to improve agricultural potentialities. The aim of this study was to develop an assessment method for crop-climate suitability that was generic enough to be applied to a wide range of issues and crops. The method proposed is based on agroclimatic indicators that are calculated over phenological periods (ecoclimatic indicators). These indicators are highly relevant since they provide accurate information about the effect of climate on particular plant processes and cultural practices that take place during specific phenological periods. Three case studies were performed in order to illustrate the potentialities of the method. They concern annual (maize and wheat) and perennial (grape) crops and focus on the study of climate suitability in terms of the following criteria: ecophysiological, days available to carry out cultural practices, and harvest quality. The analysis of the results revealed both the advantages and limitations of the method. The method is general and flexible enough to be applied to a wide range of issues even if an expert assessment is initially needed to build the analysis framework. The limited number of input data makes it possible to use it to explore future possibilities for agriculture in many areas. The access to intermediate information through elementary ecoclimatic indicators allows users to propose targeted adaptations when climate suitability is not satisfactory.

1. Introduction

Climate largely influences crop growth and development. For example, temperature affects the length of the growing season (Guerena et al., 2001), radiation deficit around meiosis causes a reduction of the number of cereal grains per spike (Gate, 1996) and a high deficit or excess of water may prevent grapes from reaching a suitable level of maturity (Dry and Coombe, 2004). Moreover, some meteorological events such as heavy rain, drought and severe frost can even lead to crop mortality. Climatic conditions can also affect the days available to perform cultural practices such as sowing and harvesting by complicating field workability (Olesen et al., 2011). Within the context of climate change and the expected increase in extreme events (IPPC 2013) we could therefore expect a rapid evolution of regional agricultural suitabilites. Consequently, the assessment of how the climate is suitable for agriculture in a given area appears essential for planners, land managers, farmers and plant breeders who can then propose and apply adaptation strategies to improve and sometimes maintain agriculture in some regions.

Agroclimatic indicators derived from climatic variables (i.e., heat degree days, frost days and the amount of rainfall over specific periods) have been widely used for this purpose. However, these indicators, provide synthetic information on the effects of climate on crop functioning. They have been mainly applied to assess the effects of climate in a given area on crop productivity, crop management and environment (Trnka et al., 2014, 2011; Rotter et al., 2013; Confalonieri et al., 2010; Mkhabela et al., 2010; Dubrovsky et al., 2009; Matthews et al., 2008; Patra and Sahu, 2007; Bootsma et al., 2005) and to study changes in species distribution (Perry et al., 2005; Desprez-Loustau et al., 2010; Malheiro et al., 2010). They are easy to use in large scale studies because of the few inputs they require to be computed. They are aggregated in some studies to assess climate or land suitability for agriculture

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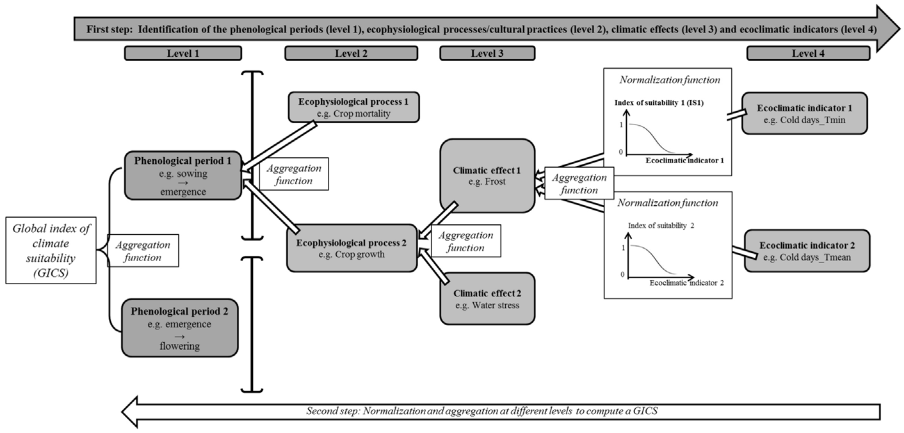

Fig. 1. Illustration of the method: identification of the different levels constituting the evaluation of climate suitability (first step) and the normalization and aggregation at different levels to compute a GICS (second step).

(Holzkämper et al., 2013; Brown et al., 2008; Hood et al., 2006; Tuan et al., 2011). Nevertheless, agroclimatic indicators often consider invariant periods (e.g., 1st January–31st July), instead of phenological periods that could help providing more accurate information about the effects of climate on particular plant processes occurring during specific crop development phases. Recent studies have actually used agroclimatic indicators calculated over phenological periods (hereby referred to as ecoclimatic indicators) (Mkhabela et al., 2010; Gouache et al., 2012; Holzkämper et al., 2013, 2011). Holzkämper et al. (2013, 2011),), in particular, developed an evaluation method where several of these indicators are calculated over the crop cycle, normalized and aggregated to derive a global index of climate suitability. The authors tested and applied this approach to the case of climate suitability for maize productivity in Switzerland. These indicators have the advantage to better fit the processes that are used to characterize maize yield and that are subject to a shift depending on temperature conditions during the year. That is why we chose to compute agroclimatic indicators over phenological rather than invariant periods in this study. Moreover, we assume that many agronomical issues other than crop productivity could be addressed on the basis of ecoclimatic indicators such as yield quality or days available to perform cultural practices (in present or future conditions). To our knowledge, the latter issues have not been yet addressed in the literature using such indicators.

The aim of this study was to develop a new assessment method of climate suitability for agriculture derived from Holzkämper et al. (2013) by improving its genericity and flexibility enough to address various issues for various crops. This method is presented in Section 2 and illustrated in Section 3 through three distinct case studies. The latter concern annual (maize and wheat) or perennial (grapevine) crops and address agronomical questions concerning climate suitability for crop cultivation according to ecophysiological criteria, days available to carry out cultural practices and yield quality. These case studies were performed for past climatic data at various sites. Because the use of the method is partly based on expert assessment, we solicited experts and their knowledge to apply the method to the different case studies. A sensitivity analysis was performed for one of the case studies in order to characterize the sensitivity of the method to expert assessment. Finally, the advantages and limitations of the method are discussed.

2. Method description

Our method is based on the aggregation of ecoclimatic indicators first developed by Holzkämper et al. (2013). Ecoclimatic indicators are agroclimatic indicators that are calculated at the scale of the crop cycle for relevant phenological periods that are defined beforehand. They make it possible to characterize the effects of climate on crop ecophysiological processes (e.g., crop growth) (Holzkämper et al., 2013), or on days available to carry out cultural practices (e.g., harvesting). These indicators can provide information about crop response to climate through ecophysiological or agronomic thresholds. According to the conceptual framework of Holzkämper et al. (2013), our method is organized into two steps (Fig. 1) which lead to design evaluation trees. The first step consists in the information of the different levels that constitute the evaluation of climate suitability. The first level corresponds to the phenological periods (phenological phases or periods around phenological stages) that may be submitted to detrimental climate effects depending on the issue in question for a given crop. The second level identifies ecophysiological processes or cultural practices that take place during these phenological periods. The third level relates to the climatic effects on them, i.e., the various stresses that climate may exert on crop or cultural practices. Finally, the fourth level concerns the ecoclimatic indicators that are used to characterize these climatic effects. The second step consists in the normalization and aggregation of the information to compute a Global Index of Climate Suitability (GICS). Ecoclimatic indicators are associated with normalization functions in order to link their values to normalized indices of climate suitability ranging from 0 to 1. These normalized indices are then aggregated using specifically designed (and adjustable) rules (Holzkämper et al., 2013). Successive aggregations are performed at the level of the climatic effects (level 3, Fig. 1), then at the level of the ecophysiological processes (or cultural practices) (level 2, Fig. 1), then at the level of the phenological periods (level 1, Fig. 1) and, finally, between phenological periods. We adopted appropriate choices of ecoclimatic indicators, normalization functions and aggregation rules according to the broad application targeted in this study. They are detailed in the following sections.

2.1. Definition of the major climatic effects and of their associated ecoclimatic indicators

We listed (Table 1) an array of climatic effects (level 3, Fig. 1) together with the ecophysiological processes or cultural practices (level 2, Fig. 1) that they affect. The ecoclimatic indicators (level 4, Fig. 1) associated with the climatic effects that they characterize are presented in Table 2.