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Climate change effects on leaf rust of wheat: Implementing a coupled crop-disease model in a French regional application

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A B S T R A C T

Leaf rust is responsible for significant wheat yield losses. Its occurrence and severity have increased in recent years, partly because of warmer climate. It is therefore critical to understand and anticipate the effects of climate change on leaf rust. Direct climate effects and indirect effects via host plants that provide a biophysical environment for disease development were both considered. The coupled STICS-MILA model simulates both crop and pathogen dynamics in a mechanistic way and their interaction is managed by two sub-models: one calculating the microclimate within the canopy and the other converting numbers of spores and lesions to affected surfaces. In this study, STICS-MILA was first calibrated and evaluated using leaf rust severity observed at various sites in France for multiple years. STICS-MILA was then run on three contrasting French sites under 2.6, 4.5 and 8.5 RCP future climate scenarios. Results focused firstly on changes in disease earliness and intensity, secondly on disease dynamics, particularly the synchronism between plant and disease developments, and finally on elementary epidemic processes.

The calibration and evaluation of STICS-MILA revealed a high sensitivity to the initial amount of primary inoculum (a forcing variable in STICS-MILA) and thus the need to properly simulate the summering and overwintering pathogen survival. The simulations in the context of future climate showed a significant change in host-pathogen synchronism: in the far future, according to RCP 4.5 and 8.5 scenarios, disease onset is expected to occur not only with an advance of around one month but also at an earlier developmental stage of wheat crops. This positive effect results from rising temperatures, nevertheless partly counter-balanced during spring by lower wetness frequency. The crop growth accelerates during juvenile stages, providing a greater support for disease development. The resulting microclimate shortens latency periods and increases infection and sporulation efficiencies, thus causing more infectious cycles. An increase of final disease severity is thus forecasted with climate change.

1. Introduction

Crop pests and diseases are responsible for direct yield losses ranging between 20 and 40% of global agricultural productivity and regularly threaten global food security (Oerke, 2006; Flood, 2010; Savary et al., 2012). However, crop losses remain poorly recognized as an important driver in matters of food security, whereas plant diseases have had an enormous impact on livelihoods throughout human history (Flood, 2010). Wheat represents one of the most highly cultivated cereal with a production area of 240 million ha worldwide (FAO FAOSTAT, average 2010–2014) about 10% of which is durum wheat, and wheat diseases remain a major constraint to wheat production (Morgonov et al., 2012). This is especially the case of leaf rust (*Puccinia triticina*), a common disease of bread wheat (*Triticum aestivum*), durum wheat (*T. turgidum var. durum*) and triticale (*X triticosecale*), that can occur wherever wheat is cultivated and under diverse climatic conditions; it thus results in regular and significant yield losses over large geographical areas (Huerta-Espino et al., 2011). Periodic leaf rust epidemics occurred in most decades of the last century (Huerta-Espino et al., 2011), making leaf rust an important disease of wheat worldwide,

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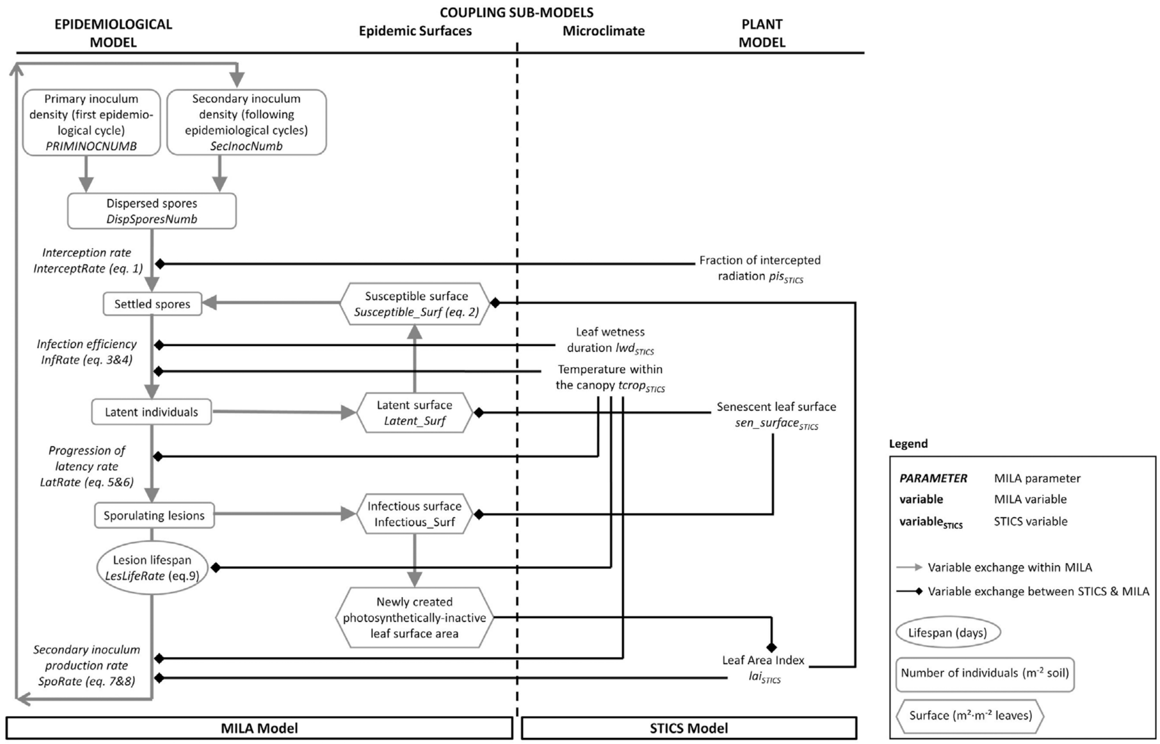

Fig. 1. MILA daily calculations and exchange variables with STICS.

increasingly impacting durum wheat production (Aoun et al., 2016). In Western and Southern Europe as well as in South America, leaf rust was the second most frequently reported disease (after powdery mildew) during the last decades, with a clear tendency towards increased occurrence in recent years (Morgounov et al., 2012). Morgounov et al. (2012) also demonstrated a clear increase in leaf rust severity both globally and across all winter wheat production regions. Those authors showed a positive correlation for Eastern Europe between rainfall and higher temperatures in March and disease severity. As climate change is expected to modify both the occurrence and development of crop diseases, Juroszek and von Tiedemann (2013) highlighted the inconsistencies between studies concerning leaf rust under climate change. While a reduction in disease pressure could be expected in Ontario, Canada (Boland et al., 2004), an increase was predicted for Germany (Racca et al., 2012), and no major trend could be found for the UK (West et al., 2012). Meanwhile, an increase and earliness of the climatic risk of infection was predicted for France (Launay et al., 2014). It is therefore critical to understand and anticipate the effects of climate change on leaf rust occurrence and intensity, especially in a context of reduced use of pesticides proven to negatively impact both environment and human health (Kim et al., 2017).

A better understanding of climate change impacts requires considering both their direct and indirect effects via host plants through the microclimate and physical support for disease development they provide (Calonnec et al., 2013). Moreover, examining impacts at the level of epidemiological processes would make it possible to identify the relevant triggers to solve agronomic issues. Modeling approaches can provide information on crop disease dynamics in a future climate under many different conditions and can take account of the complexity of climate-host-pathogen interactions. Among existing models for simulating disease development on crops, mechanistic ones provide the most relevant approach when coupled with a dynamic crop model, given that the whole host-pathogen system is being driven by climate. It is assumed that the response of epidemiological processes to climate variables remains the same whether climate variables belong to the actual variability of the range of anticipated climate change. Such mechanistic models also assume inoculum survival during the fallow period, and that there is no change in cultivars for genetic protection against the disease. They make it possible to simulate the complex interactions between the two biological systems at a given time step (often daily) (Pangga et al., 2011). They dynamically reproduce their developments and, therefore, their synchrony since the host biomass and surface offer a more or less trophic support for the pathogen, the microclimate within the canopy, and the damage caused by the pathogen to host functioning. Such models have been developed and coupled, including the mechanistic STICS-MILA model devoted to fungal pathosystems (Caubel et al., 2012, 2014). STICS-MILA originality consists in its general applicability to a range of airborne fungal pathogens responsible for foliar diseases (Caubel et al., 2012, 2014), as well as its ability to account for different plant factors, and particularly microclimate, in a dynamic way during the crop cycle. MILA conceptual design was described in Caubel et al. (2012): each epidemiological process is modelled by a set of several response functions to climate, microclimate within the canopy, plant growth and development, and trophic status variables.

This paper aims to use STICS-MILA to simulate climate change impacts in the case of wheat-leaf rust pathosystem. In a first step, the dynamic coupling of MILA to STICS is briefly recalled in order to highlight the direct and indirect effects (through the canopy) of the climate on the epidemic cycle; then a sensitivity analysis is carried out on the parameters of MILA in order to calibrate the model only on the most important ones. The model is then calibrated and evaluated using a network of 14 experiments covering a broad climate variability, which makes it possible to establish the performance of the model. The model is then used to simulate CC impacts on the development of leaf rust in three contrasting French sites under 2.6, 4.5 and 8.5 RCP scenarios. These overall impacts are dissected by showing how climate change differentially modifies specific processes depending on the site x period.