Terrestrial fluxes in major Indian agroecosystems: A numerical study using the Community Land Model (CLM5)

by

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Abstract

Agroecosystems cover nearly 50% of the land in India, with wheat and rice accounting for approximately 80% of the farmlands. Several site-scale investigations explored terrestrial carbon, water, and energy fluxes (terrestrial fluxes – from now in in the thesis) within Indian agroecosystems (Patel et al., 2011 and 2021; Bhattacharya et al., 2013). However, these do not accurately reflect the extensive and climatically varied farming environments present in India. Consequently, the primary aim of this study is to quantitatively understand the long-term trends and regional variations in yield, growth parameters, and terrestrial fluxes of Indian agroecosystems. Land surface models (LSMs) are valuable tools for such studies because they can be used to conduct numerical experiments to examine the effects of natural and human drivers on agroecosystems across regional and global scales. The Community Land Model version 5.0 (CLM5) is a state-of-the-art LSM that has been widely used to study agroecosystems. However, the depiction of Indian agroecosystems in CLM5 is not realistic leading to biases in the simulation of yield and irrigation compared to observed data (Lombardozzi et al., 2020; Mathur and AchuthaRao, 2020). The primary challenge in improving the representation of Indian crops is the scarcity of publicly accessible crop data necessary for model calibration and evaluation (Gahlot et al., 2020).

This thesis aims to investigate the spatio-temporal variability in crop phenology, and terrestrial fluxes across Indian agroecosystems and the role of natural and anthropogenic drivers in the observed variability. The specific objectives are outlined as follows: (1) to understand the crop phenology of Indian agroecosystems from site-scale observational data, (2) to improve the CLM5 model using site-scale observations, (3) to evaluate the improved CLM5 model at a regional scale, (4) to estimate the regional and inter-annual variability of crop growth parameters and terrestrial fluxes within Indian agroecosystems and the role of various drivers using CLM5 model, and finally (5) to evaluate the improved CLM5 model against the state-of-the-art LSM representing Indian agroecosystems.

First, Chapter 2 addresses objective 1 by attempting to solve the main bottleneck in accurately simulating Indian agroecosystems, specifically the absence of publicly accessible crop datasets that hinders our ability to quantitatively understand and model agroecosystems. This thesis compiled a novel crop dataset focusing on two significant crops in India: rice and wheat. This was done by digitising the archived masters and doctoral theses from agricultural universities across India. The crop dataset spans from 1970 to 2020, encompassing site-scale

observations across 47 sites and 147 growing seasons. This dataset served as the foundation for calibrating the CLM5 model. The LAI data from the site-scale observations shows that the major growing season for rice is June to October and for wheat it is November to April. Major observations from the data analysis are that rice and wheat have a statistically significant increasing trend in yield (38 kg/ha/yr – 97.4% increase, for rice and 34 kg/ha/yr – 83% increase, for wheat) over the 1970-2020 period. A statistically significant trend in the length of the growing season for wheat crop is observed from the dataset; harvest dates extended by ~14 days over the 50-year period ($p<0.1$).

Chapter 3 addresses objective 2 where the CLM5 model is improved and evaluated against site-scale observations. The default version of the CLM5 model failed to replicate the crop phenology and growth seen in the site-scale observations. To address this drawback, the crop module in CLM5 is calibrated and validated at a point scale using the novel Indian crop dataset compiled in this thesis. The representation of crops in CLM5 is improved through a two-step approach: (1) calibrating the growing season and crop parameters specific to crop growth; (2) integrating regional variations in crop growth parameters, which is crucial for a country like India with its diverse climate conditions. The calibration of the growing season and crop parameters involved 30 sensitivity simulations. I evaluated the base temperature used in calculating the growing degree days for the crop at each site to account for the regional variability in crop growth. One hundred fifty sensitivity experiments are carried out to establish a relationship between latitude and base temperature for a crop. The calibration of the model significantly improved the simulation of the growing season, crop physiological parameters, crop phenology, and yield compared to site scale observations. RMSE for Leaf Area Index (LAI) in wheat and rice reduced by ~50%. The RMSE in yield for wheat and rice reduced by ~40% and ~60%, respectively. RMSE of the growing season length for the wheat crop reduced by ~75%.

Chapter 4 addresses objective 3 where the improved CLM5 is evaluated at regional scale by conducting numerical simulations for the 2000 to 2014 period. For this purpose, the values of yield, irrigation amounts and patterns, and terrestrial fluxes simulated by the default and improved models are compared against multiple data sources. Results show that the CLM5 improvements reduce the RMSE in rice yield by 25% and the RMSE in GPP by about 50%. Major improvements are also observed in water and energy fluxes at the regional scale after improvements to the crop module. The irrigation pattern and amount irrigated saw a considerable improvement and are now closer to observations. The findings from the site-scale and regional-scale assessment of the improved model underscore the importance of employing region-specific crop parameters to accurately simulate agroecosystems and regional land surface processes.

Chapter 5 addresses objective 4. The thesis examines the regional and inter-annual variability in crop yield and terrestrial fluxes within Indian agroecosystems, utilizing a multi-decadal simulations that covers the period from 1970 to 2014. Furthermore, numerical experiments are conducted to investigate the impact of two natural and two agricultural management factors on the observed trends in crop physiology and terrestrial fluxes throughout the simulation period. The LAI, yield, total dry matter of wheat and rice, and the carbon fluxes associated with the crops in their respective growing regions demonstrated statistically significant increasing trends ($p<0.05$) from 1970 to 2014. The numerical experiments revealed that management practices predominantly drive the upward trend, while the rise in CO_2 is also a significant driver. The application of nitrogen fertilization had a significant impact on rice yield, which is cultivated in warm and wet seasons. Irrigation primarily influenced wheat yield, which is grown in dry and cold seasons. Even with the detrimental effects of climate on crop growth and terrestrial fluxes, higher CO_2 levels and increased human activities, like fertilization and irrigation, alleviated these challenges, leading to a rise in crop yields over the study period.

Chapter 6 of the thesis performs a comparative analysis of the CLM5 model and the Integrated Science Assessment Model (ISAM), which is the only other land surface model calibrated and assessed (Gahlot et al., 2020) to simulate the Indian crops to the best of my knowledge. This thesis has two advantages over the Gahlot et al. (2020). First, the CLM model is calibrated using data from 14 sites covering 33 growing seasons. Second, this study investigates both rice and wheat as opposed to Gahlot et al. (2020) who look at only spring wheat. Numerical experiments conducted in Chapter 5 with CLM5 were repeated using the ISAM model. The findings demonstrate that CLM5 simulates the observed variation in growing season length more precisely with an RMSE of 14 days, in contrast to the ISAM model, which has an RMSE of 28 days. The wheat yield in CLM5 shows a strong sensitivity to nitrogen fertilization, while in ISAM, the yield demonstrates a significant sensitivity to irrigation. The AR/GPP ratio exhibits variability in CLM5, while it remains constant in ISAM. The ratio in ISAM is comparatively low when evaluated against the values reported in multiple studies. Examining climate and human management impacts on carbon fluxes reveals that although net primary productivity (NPP) trends in CLM5 and ISAM are similar, the effects of human management practices on carbon fluxes vary considerably. Nitrogen fertilization has a significant impact in

CLM5, while irrigation shows a more substantial effect in ISAM. Both models have a lot of scope for improvement. ISAM is simulating the observed maximum LAI at the sites but the regional variability in growing length in observations is not captured by the model. ISAM can incorporate dynamically varying crop parameters like T_{base}, to capture the regional variability in crop growth.

This is the first study to address the long-term spatial and inter-annual variability of agroecosystem physiological parameters and their terrestrial fluxes in India using a robustly calibrated LSM. The results of the thesis highlight the importance of agroecosystems in India and show the significant impact they have on terrestrial fluxes. The accurate representation of agroecosystems and their management practices is necessary in simulating the water and energy fluxes accurately. The agroecosystems have broader implications for regional climate, hydrology, and food security under changing climatic conditions.