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Assimilating Leaf Area Index and Soil Moisture into the WOFOST Model for Improved Maize (Zea mays L.) Yield Estimation

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1. Introduction

- Yield estimation and forecasting continue to rely on traditional approaches, such as field surveys, and statistical models using agrometeorological data
- The lack of timely, accurate, and large-scale crop growth monitoring, assessment, and yield forecasting has prompted East African decision-makers to intensify their efforts to implement crop monitoring and yield forecasting systems.
- Further work is needed to improve the integration of seasonal crop acreage estimation and crop yield forecast with satellite observations and to improve access to more accurate and timely crop monitoring and yield forecasting tools.

Objective:

- The main objective of this study was to estimate regional maize yield and improve accuracy by jointly assimilating LAI and SM data from remote sensing observation.

2.1. Study Area

- This study was carried out in Ethiopia's main maize-growing regions, where rain-fed agriculture is crucial.
- Most smallholder farmers in these areas depend on seasonal rains for their crops.
- The study encompasses 28 administrative zones across seven regional states (Amhara, Benishangul Gumuz, Central Ethiopia, Oromia, Sidama, South Ethiopia, and Southwest Ethiopia), covering an area of 410,149.19 km².

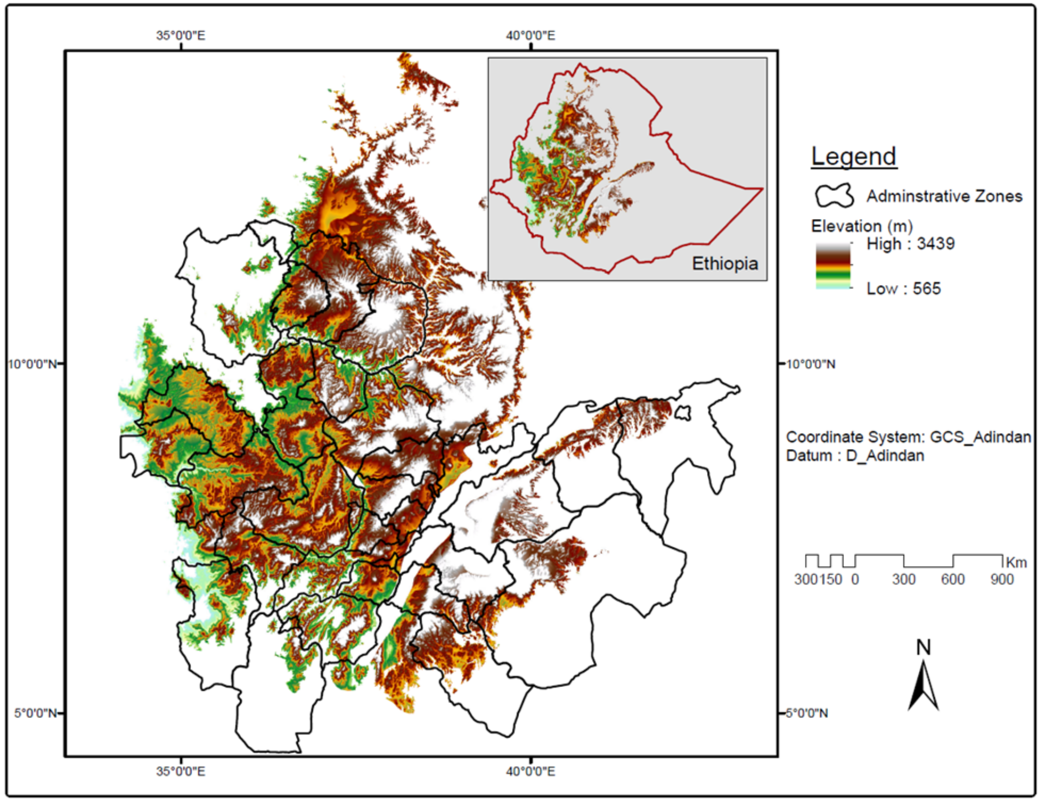


Figure 1. Map of the study area

2.2. Data sources

- Daily weather data, obtained from the NASA Power project
- Soil data was obtained from the ISRIC-WISE database
- Crop management data, including sowing dates, fertilizer rate, application time, and harvesting details from the TAMASA field observation data.
- Crop mask from world cereal crop maps
- Crop yield data from CSA
- MODIS LAI dataset and
- Soil Moisture Active Passive (SMAP) mission’s SM product

2.3. Methods

- The WOFOST model, was used to simulate maize AGB, based on the Python Crop Simulation Environment (PCSE) package.
- Model sensitivity analysis using **Sobol Sensitivity Analysis**
- Model optimization using the **SUBPLEX optimization algorithm.**
- A sequential DA using the **EnKF algorithm** was applied
- Three DA strategies were implemented for estimating yield: assimilating LAI, assimilating SM, and jointly assimilating LAI and SM (jointing, tasseling, and silking stages).
- The estimated yield derived from the open loop simulation and the three DA methods were compared with the official yield data from CSA.
- The errors were quantified: **coefficient of determination (**R^2**), Root Mean Square Error (RMSE), and normalized RMSE (NRMSE).**

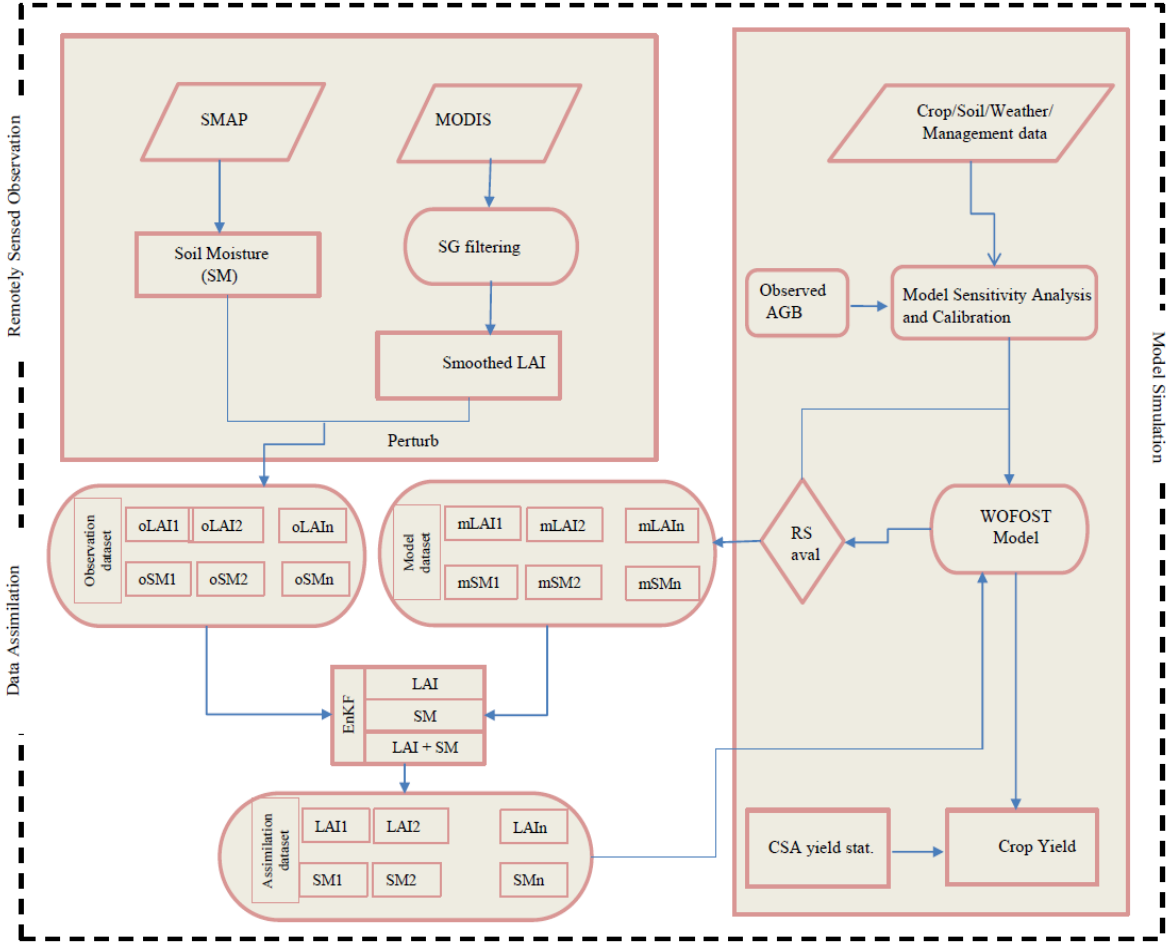


Figure 2. The technical framework of maize yield estimation (Note: EnKF refers to ensemble Kalman filter Algorithm).

3.1. Model sensitivity analysis and calibration

- Eight crop parameters were selected for sensitivity analysis
- The LAImax first-order sensitivity analysis showed **that TSUM1(temperature sum from emergence to anthesis**) was more sensitive to LAImax (sensitivity coefficients was 0.96) (Figure 3a).
- The TSWO (weight of storage organs) first-order SA showed that **TSUM1, SPAN (life span of leaves) and CVO(efficiency of conversion into storage organ)** were more sensitive to TSWO (sensitivity coefficients: 0.25, 0.43 and 0.15 respectively) (Figure 3b).
- The sensitive crop parameters: such as TSUM1, TSUM2, SPAN and CVO) were then adjusted using the SUBPLEX optimization algorithm.

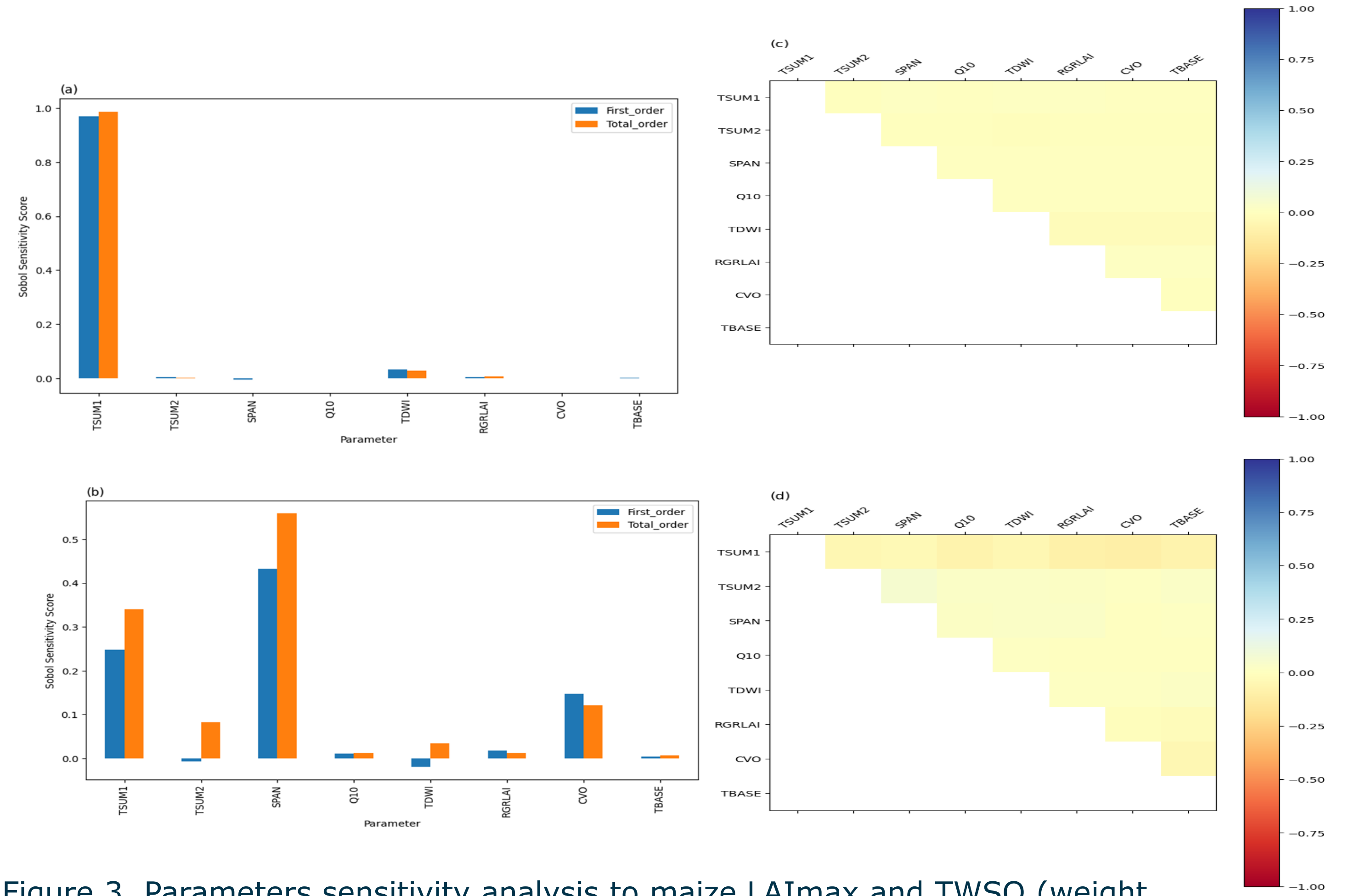


Figure 3. Parameters sensitivity analysis to maize LAImax and TWSO (weight of storage organs) respectively, using first-order sensitivity coefficient (a, b) and second order sensitivity coefficient (c, d)

3.2. Effect of assimilating LAI and soil moisture observations into WOFOST model

- DA was proposed in this study to evaluate the impact of the three assimilation strategies for improving maize yield estimation
- LAI and SM were used as assimilation variables, and seven sequential assimilations were performed using the EnKF algorithm on selected dates(i.e., jointing, tasseling, and silking stages).
- In the EnKF assimilation process, **selected parameters sensitive to LAI and SM** status were considered to conform to a Gaussian distribution, with the standard deviation determined empirically from previous studies.
- Each ensemble member from the parameter distribution was sampled, overriding its default value.

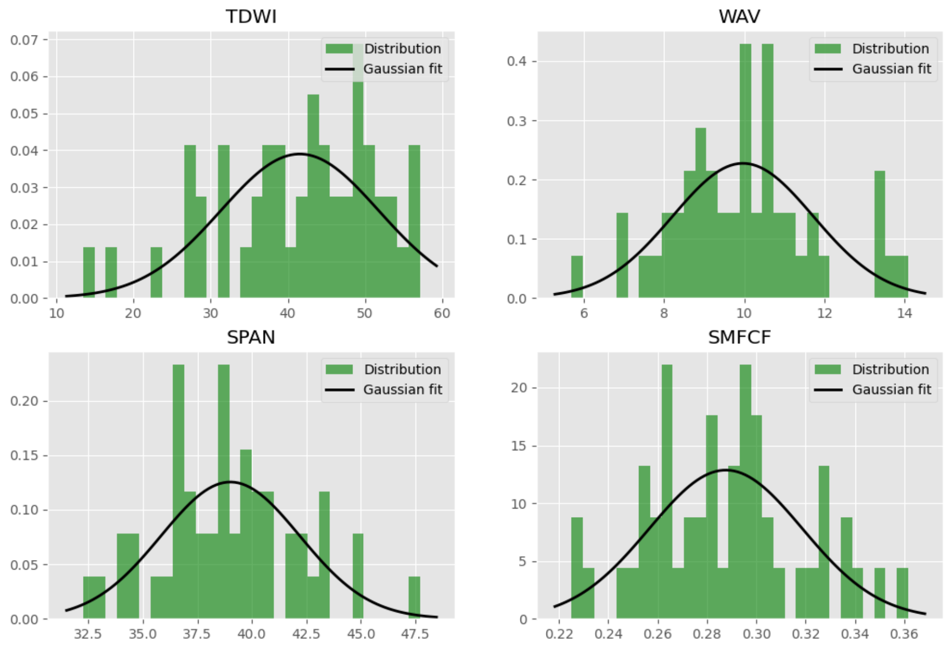


Figure 5. Parameters distributions and gaussian fit curves when sampling in EnKF algorithm.

3. Results

- The LAI simulation results from the original WOFOST model were higher than those from the MODIS products, indicating that the WOFOST model tends to overestimate both LAI and, consequently, AGB.
- Assimilating observed LAI reduces discrepancies between the simulated and observed LAI during the growth period

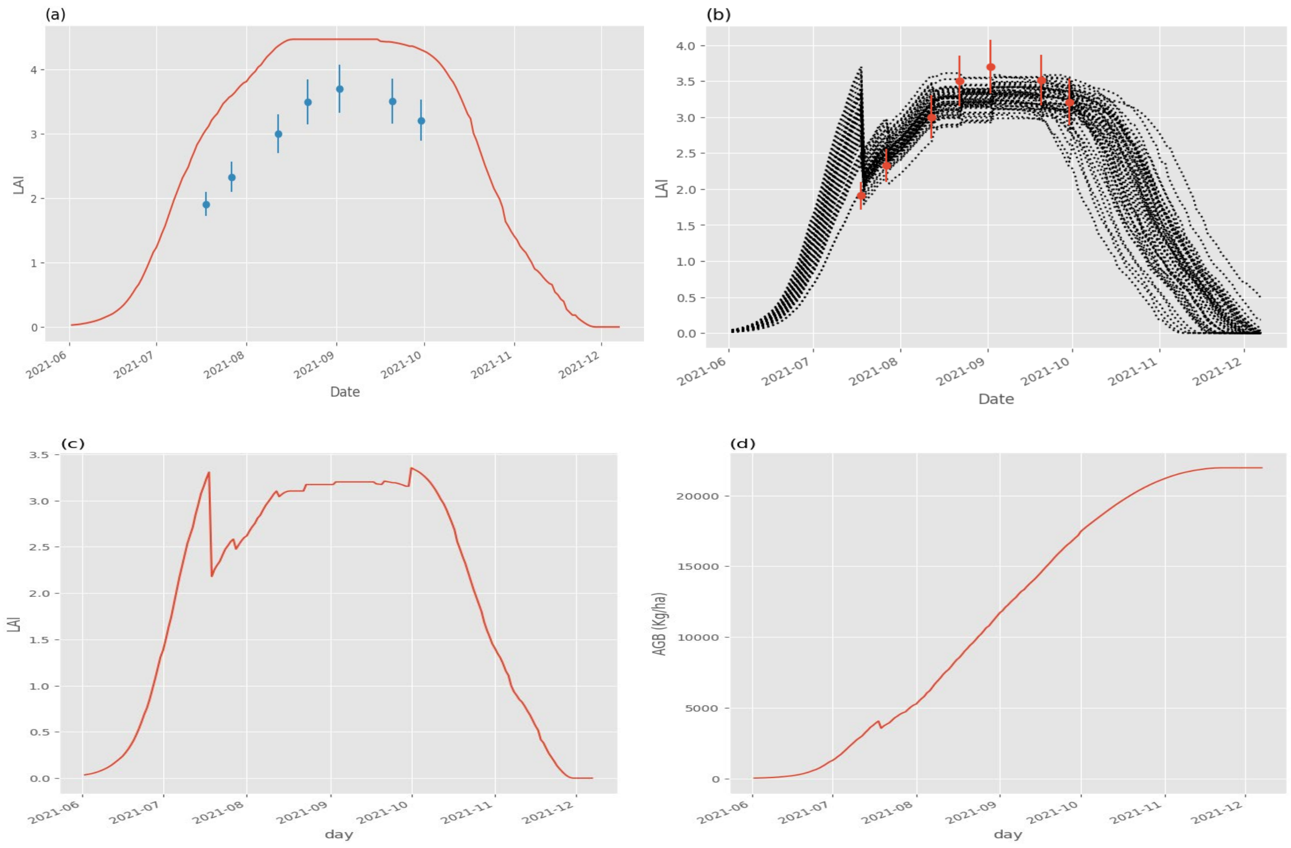


Figure 6. The LAI simulations of the WOFOST with open loop and assimilation of MODIS LAI (a, b), Estimated development of LAI and AGB using assimilation of MODIS LAI (c, d)

3. Results

- The open-loop WOFOST simulation (Figure 7a), which was applied at water-limited level, has a tendency to underestimate the root zone simulated SM,
- Assimilating SM observation with the EnKF narrows the gap between the simulated and observed SM, by re-estimating the simulated SM values (Figure 7b).

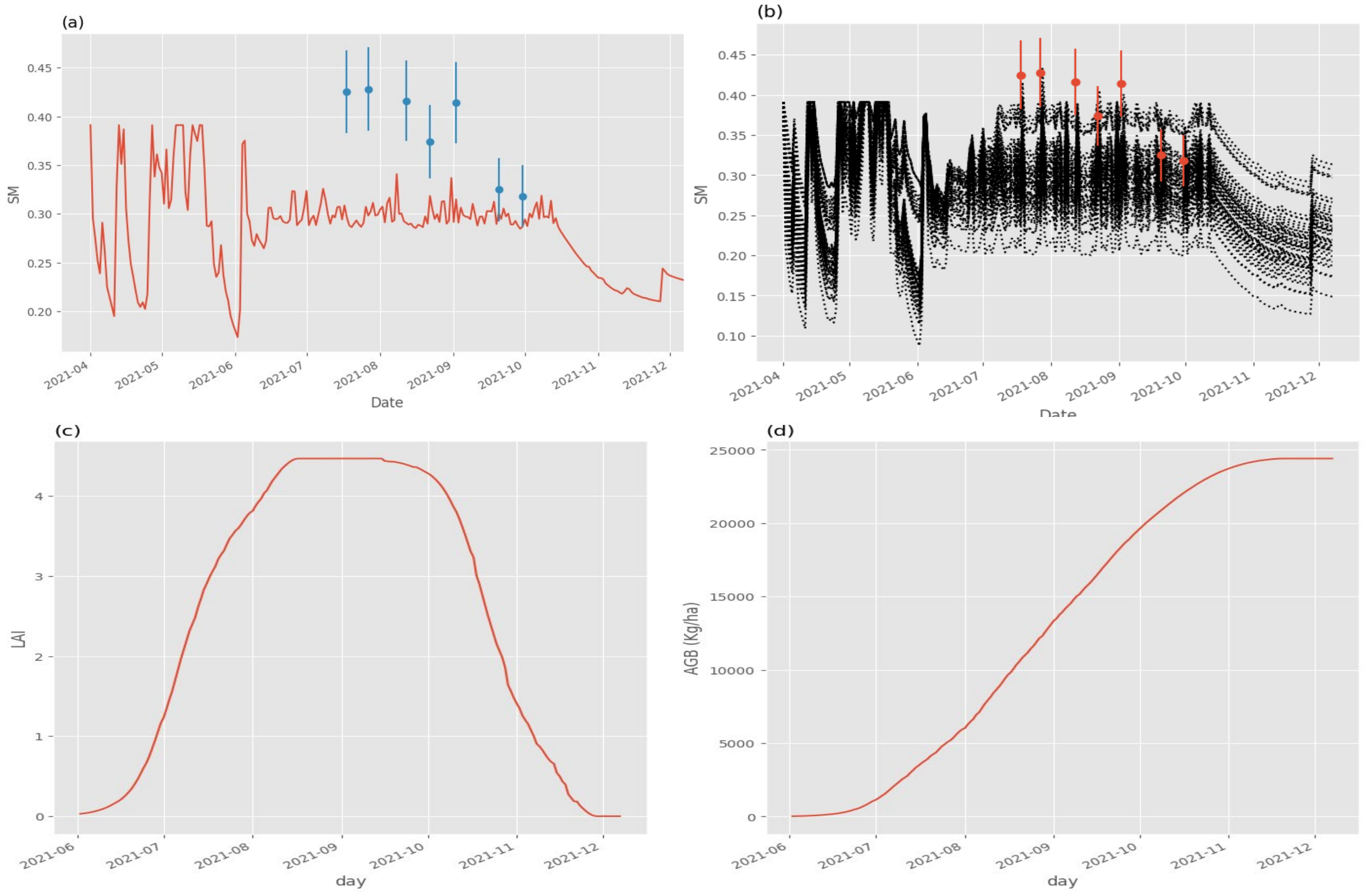
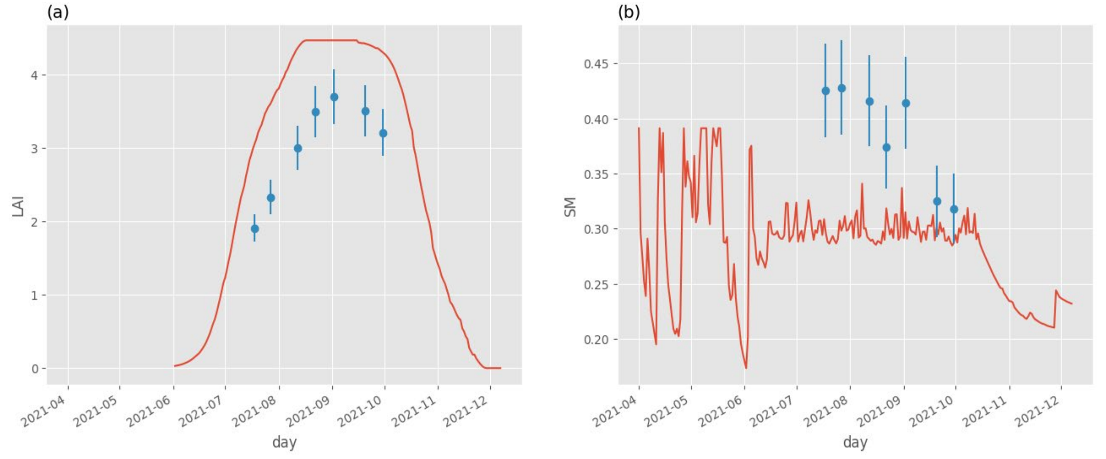


Figure 7. The SM simulations of the WOFOST with open loop and assimilation of SMAP SM (a, b), Estimated development of LAI and AGB using assimilation of SMAP SM (c, d)

3. Results

- The results also showed that joint assimilation of LAI and SM observations using the EnKF method reduces discrepancies between simulated and observed values for both LAI and SM.
- The method included more information from the observations than the WOFOST simulation.



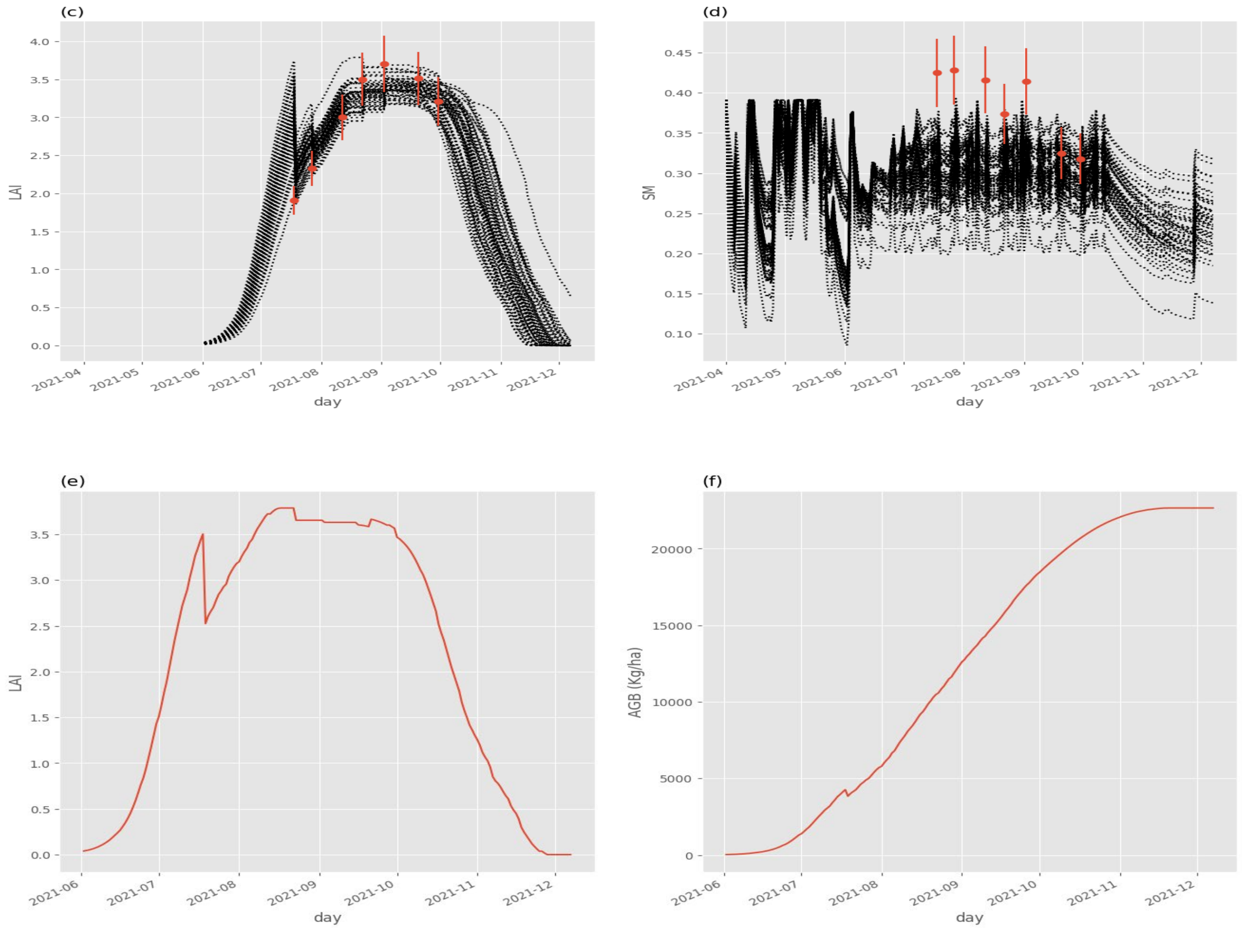


Figure 8. The LAI and SM simulations of the WOFOST with open loop (a, b), with assimilation of MODIS LAI and SMAP SM (c, d), Estimated development of LAI and AGB using joint assimilation of MODIS LAI and SMAP SM (e, f).

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3.3. LAI and soil moisture assimilation for estimating maize yield using data assimilation approaches.

- The results showed that joint DA with observed LAI and SM significantly improved the performance accuracy of maize yield estimation compared with the DA with only LAI, or SM and the open-loop simulation
- Results showed that the accuracy of predicted maize yield improved when assimilating LAI data with the WOFOST model, compared to assimilating SM data with the WOFOST model (Figures 9b and 9c).

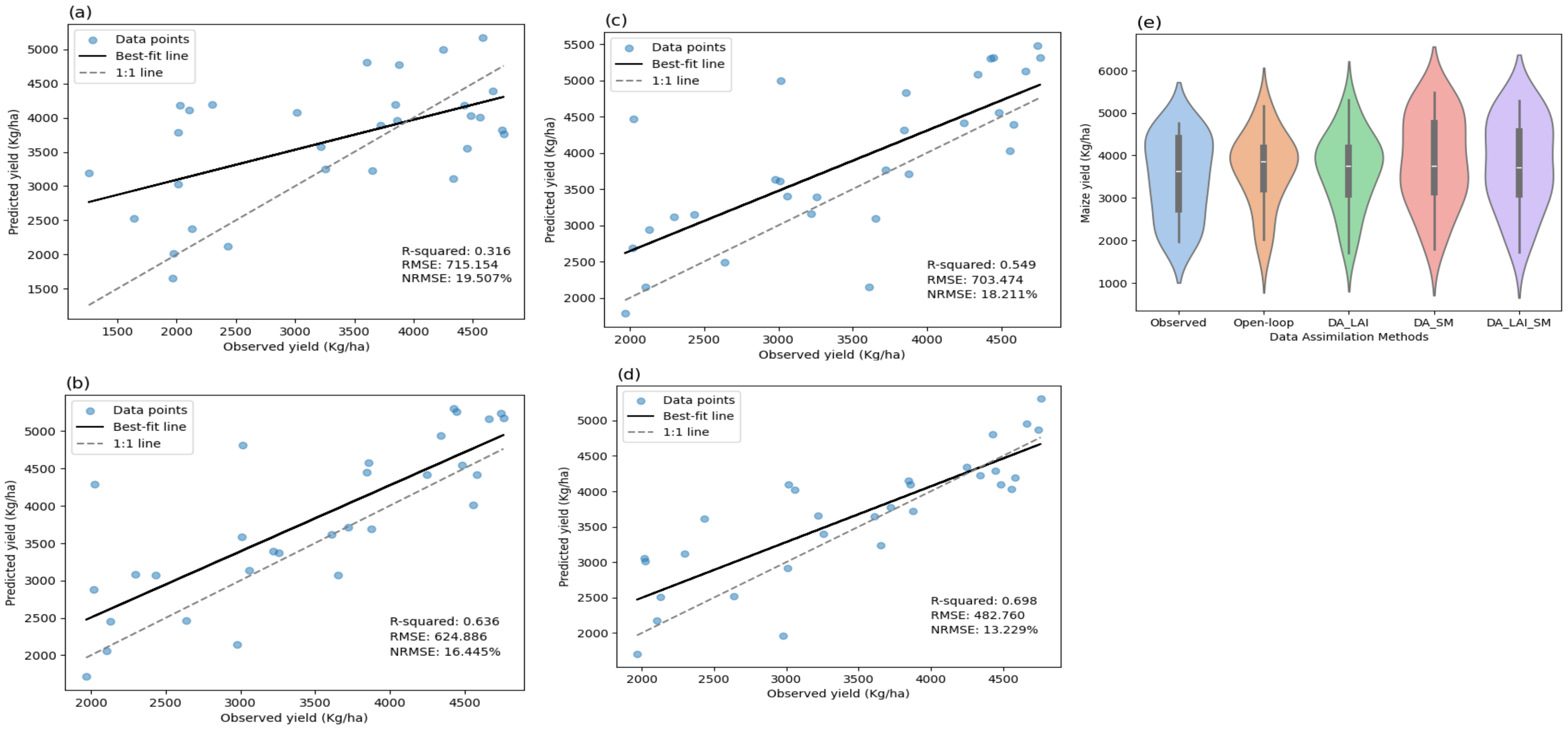

Figure 9. Validation of the yield estimation results: (a) without DA, (b) wit DA of LAI, (c) with DA of SM (d) with Joint DA of LAI and SM, and (e) yield violin plot.

4. Conclusion

- Joint assimilation has greater potential for regional crop yield estimates compared to univariate observation data.
- Integrating remotely sensed observation data with crop growth models is effective for predicting crop yields at a regional scale.

Limitations of the study and Future research:

- Higher resolution earth observation data, better parameter values, and additional data such as evapotranspiration (ET) could enhance performance.
- Other datasets like ET and AGB are needed to improve data assimilation.
- WOFOST model's regional implementation cannot rely solely on remotely sensed data
- In put data such as weather data and model structure contribute to uncertainties in yield simulations.

Acknowledgments

- **The EO Africa Initiative, ESA**, for providing me Research Fellowship and for providing the Innovation Lab-EO Africa cloud computing platform
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- NASA Langley Research Center (LaRC) POWER Project for providing daily weather data

Thanks for your attention !

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