Effect of Remotely Sensed Vegetation in Hydrology and Water Quality Predictions: New Evidence from Large-scale Watershed Modeling

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Abstract

Traditional watershed modeling often overlooks the role of vegetation dynamics. While past studies indicate possible improved hydrologic predictions by increasing the physical realism of vegetation dynamics in process-based models, there has been little quantitative evidence to support similar improvements in water quality predictions. To fill this knowledge-gap, we recently applied a modified Soil and Water Assessment Tool (SWAT) to quantify the extent of improvements that the assimilation of remotely sensed Leaf Area Index (LAI) would convey to streamflow, soil moisture, and nitrate load simulations across a 16,860 km2 agricultural watershed in the midwestern United States. We modified the SWAT source code to directly insert spatially distributed and temporally continuous LAI estimates from Moderate Resolution Imaging Spectroradiometer (MODIS). Compared to a "basic" traditional model with limited spatial information, our LAI assimilation model (i) significantly improved daily streamflow simulations during medium-to-low flow conditions, (ii) provided realistic spatial distributions of growing season soil moisture, and (iii) substantially reproduced the long-term observed variability of daily nitrate loads. Further analysis revealed that assimilation of MODIS LAI data corrected the model's LAI overestimation tendency, which led to a proportionally increased rootzone soil moisture and decreased plant nitrogen uptake. With these new findings, our study confirms that assimilation of MODIS LAI data in watershed models can effectively improve both hydrology and water quality predictions.

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BACKGROUND

The few recent studies assimilating remotely sensed vegetation data (e.g., Leaf Area Index, LAI) in traditional watershed modeling practices invariably showed improved model predictability. Yet, we identified two major knowledge-gaps that require targeted investigations:

(1) Previous studies were predominantly focused on hydrologic processes (Kumar et al., 2019) (https://doi.org/10.1175/JHM-D-18-0237.1). Although studies involving water quality simulations evaluated the potential effect of improved LAI on sediment yield (Ma et al., 2019) (https://doi.org/10.1016/j.jhydrol.2019.01.024), the extent of such effects on nutrient (e.g., nitrate) loads – the most critical issue in agricultural watersheds from water quality management standpoint – is still unknown.

(2) Evaluations conducted in the previous hydrologic studies were mostly limited to vertical water flux and storage simulations (e.g., evapotranspiration and soil moisture), with very little emphasis on the watersheds' cumulative response to downstream waters (i.e., streamflow).

In this study, we intended to fill these knowledge gaps by assimilating Moderate Resolution Imaging Spectroradiometer LAI data (MODIS MCD15A3H) (Myneni et al., 2015) (https://lpdaac.usgs.gov/products/mcd15a3hv006/) into the Soil and Water Assessment Tool (SWAT) (Neitsch et al., 2011) (https://swat.tamu.edu/media/99192/swat2009-theory.pdf).

RESEARCH OBJECTIVE AND METHODOLOGY

The specific objective of this study was to quantify the extent of improvements that the assimilation of MODIS LAI data would convey to streamflow, soil moisture, and nitrate load simulations at a daily timescale. Another unique contribution of our study was a new, highly efficient SWAT source code, which can perform multisource, multivariate assimilation of remotely sensed data regardless of watershed sizes and geolocations.

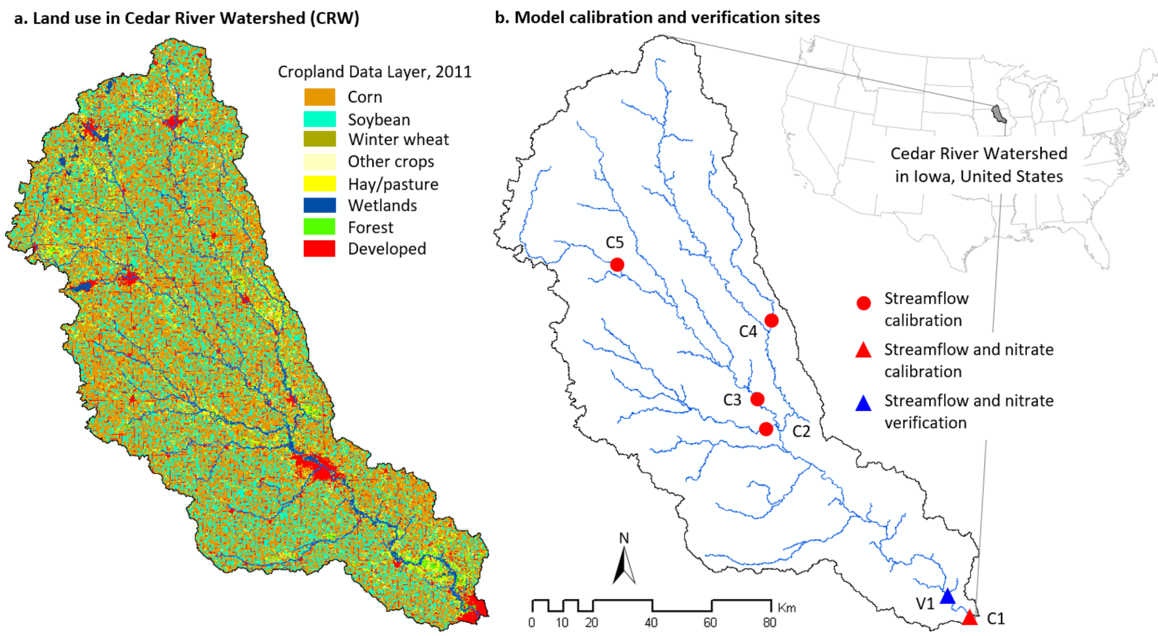

Fig 1. *The 16,860-km^2 Cedar River Watershed in Iowa, United States.*

We developed two contrasting model configurations to evaluate the effect assimilating MODIS LAI data on simulated streamflow, soil moisture, and nitrate load:

(1) The basic model: LAI was simulated by the model based on input land use and associated biophysical parameters – a common approach in watershed modeling. This was our baseline to measure the degree of improvement in model results in the subsequent configuration;

(2) The LAI-assimilation model: the same setup as in the basic model, except MODIS LAI was directly inserted by replacing the simulated LAI values in each of the spatial units of the model (e.g., hydrologic response units or subbasins).

RESULTS: EFFECTS OF LAI ON HYDROLOGY

Right answers for wrong reasons: Incorrect vegetation dynamics yield pseudo-accurate streamflow simulations

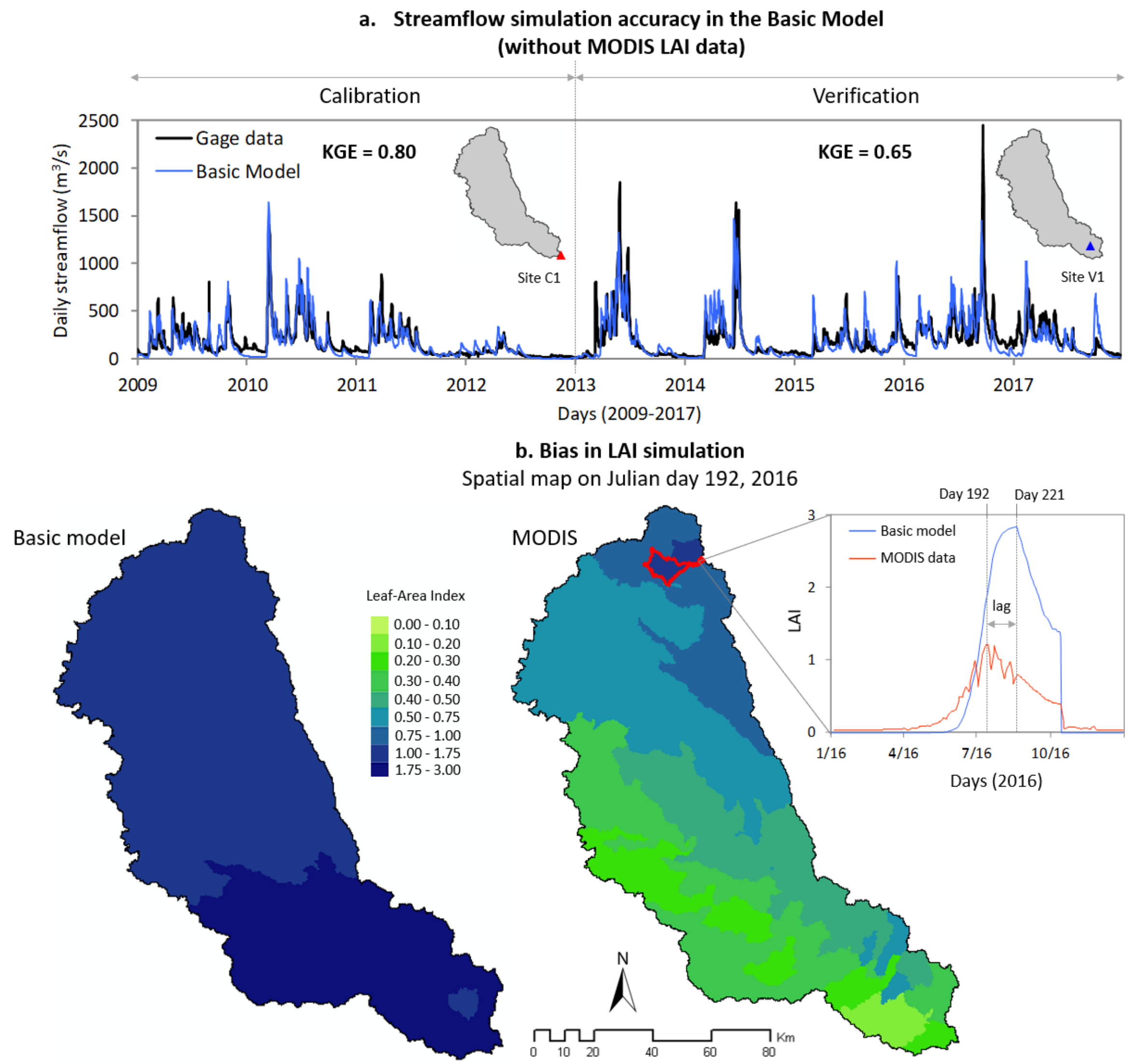

Fig 2. *(a) Reasonably good daily streamflow simulation despite (b) large bias in LAI.*

LAI data assimilation significantly improves baseflow

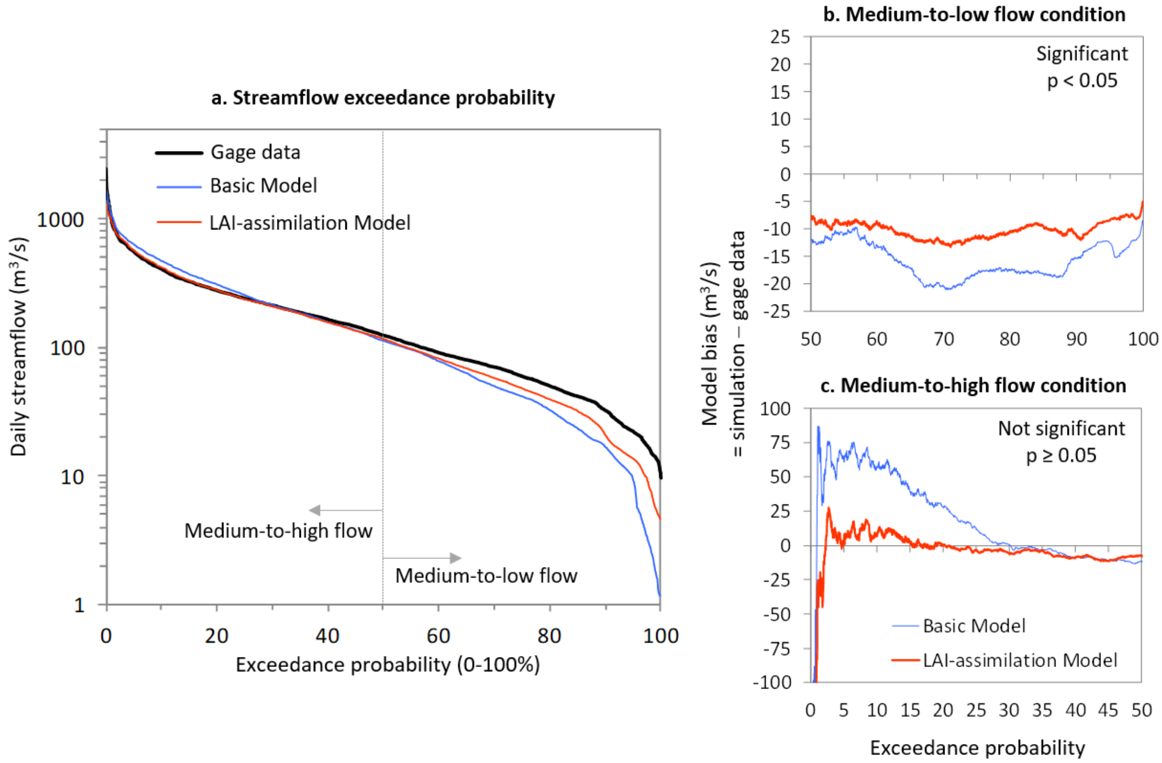

Fig 3. *Exceedance probability at different flow regimes.*

LAI data assimilation reduces the bias in water balance

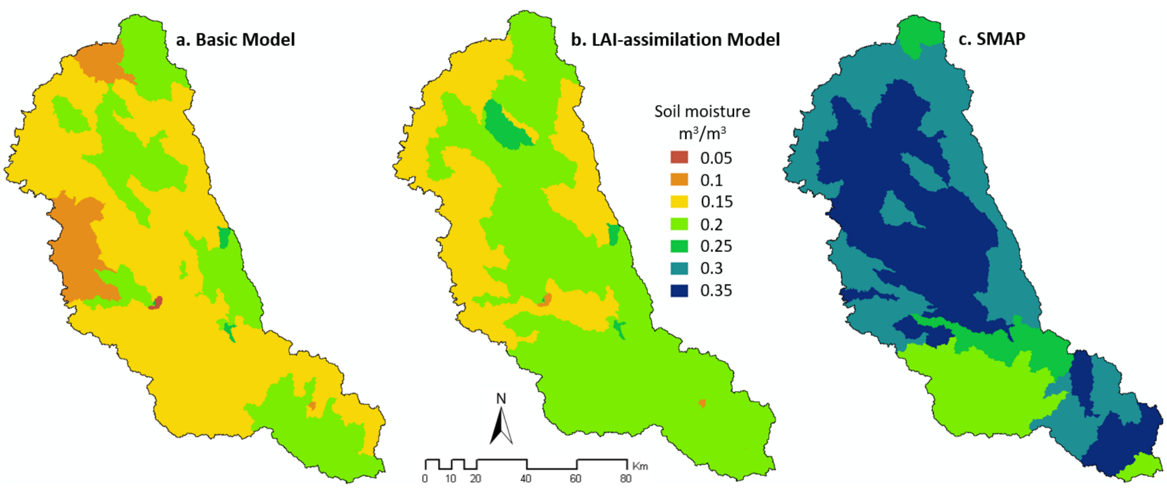

Fig 4. *Comparison of daily average rootzone soil moisture across the 2016 crop growing season (June–August): (a) Basic model, (b) LAI assimilation model, and (c) SMAP data. The values represent wetness (m3/m3) in the top 100 cm of the soil profile.*

RESULTS: EFFECTS OF LAI ON WATER QUALITY

LAI data assimilation improves daily Nitrate load simulations

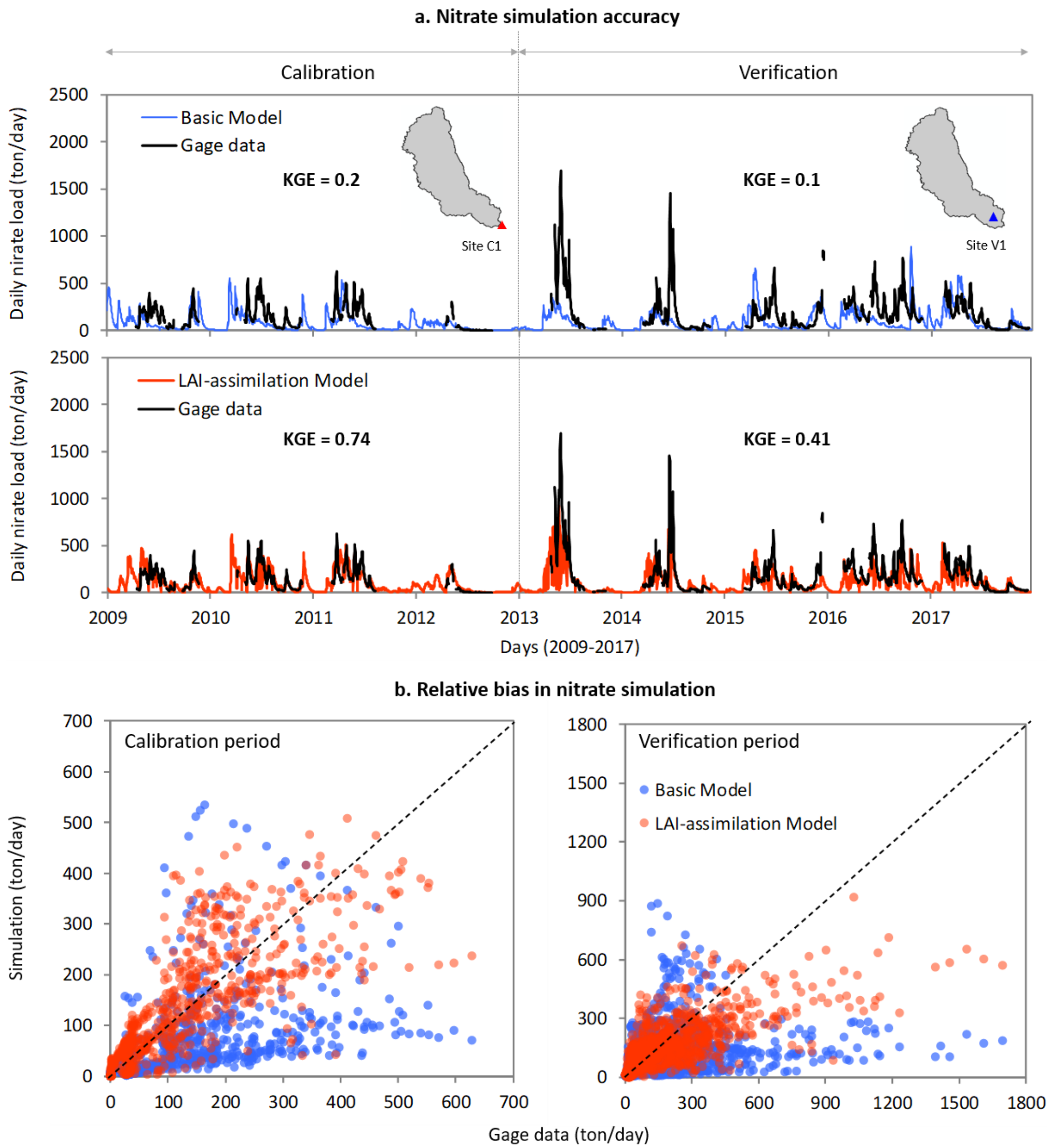

Fig 5. *Effect of MODIS LAI data on the simulation of daily nitrate loads. (a) Improved accuracy as a result of assimilating MODIS LAI data. (b) The scatterplot shows the relative change of bias in the basic and LAI assimilation configurations separately for calibration and verification periods. Proximity to the 1:1 line indicates reduced bias relative to gage station in-situ nitrate data.*

SUMMARY

1. The basic model gave right answers for wrong reasons, with reasonably good daily streamflow simulation despite a large bias in LAI. The accuracy of daily streamflow simulation improved throughout the nine-year period. However, this improvement was significant during medium-to-low flow conditions.
2. The LAI assimilation model adopted a physically realistic water balance by increasing rootzone soil moisture storage, therefore improving the model's spatial consistency with reference estimates (from the SMAP satellite mission).
3. Assimilation of LAI data into our watershed model substantially improved nitrate load simulations, reproducing long-term in-situ observations at a daily timescale. Our study is the first to show such an effect.

A recent publication by Rajib et al. (https://doi.org/10.3390/rs12132148) provides more details on this work.

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ABSTRACT

Traditional watershed modeling often overlooks the role of vegetation dynamics. While past studies indicate possible improved hydrologic predictions by increasing the physical realism of vegetation dynamics in process-based models, there has been little quantitative evidence to support similar improvements in water quality predictions. To fill this knowledge-gap, we recently applied a modified Soil and Water Assessment Tool (SWAT) to quantify the extent of improvements that the assimilation of remotely sensed Leaf Area Index (LAI) would convey to streamflow, soil moisture, and nitrate load simulations across a 16,860 km2 agricultural watershed in the midwestern United States. We modified the SWAT source code to directly insert spatially distributed and temporally continuous LAI estimates from Moderate Resolution Imaging Spectroradiometer (MODIS). Compared to a "basic" traditional model with limited spatial information, our LAI assimilation model (i) significantly improved daily streamflow simulations during medium-to-low flow conditions, (ii) provided realistic spatial distributions of growing season soil moisture, and (iii) substantially reproduced the long-term observed variability of daily nitrate loads. Further analysis revealed that assimilation of MODIS LAI data corrected the model's LAI overestimation tendency, which led to a proportionally increased rootzone soil moisture and decreased plant nitrogen uptake. With these new findings, our study confirms that assimilation of MODIS LAI data in watershed models can effectively improve both hydrology and water quality predictions.