Understanding ecosystem gross primary productivity, evapotranspiration, and water use efficiency of maize using ISBA-A-g_s land surface model over temperate and tropical semi-arid climates

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Abstract

Water use efficiency (WUE) links carbon assimilation and water loss and is an important indicator of ecosystem functioning under changing hydroclimatic conditions. Process-based land surface models (LSMs) provide a framework for simulating carbon-water interactions, but their ability to reproduce ecosystem-scale WUE across contrasting climates remains insufficiently evaluated. This study assesses the performance of the ISBA-A-g_s land surface model, implemented within the SURFEX platform, in simulating gross primary productivity (GPP), evapotranspiration (ET), and WUE (GPP/ET) for maize under temperate conditions in

France (FR-Lam) and tropical semi-arid conditions in India (Ind-IITH). The model was driven by site-specific meteorological and vegetation data across six growing seasons at FR-Lam under sprinkler irrigation and two growing seasons at Ind-IITH, representing monsoon and winter crops under alternate furrow irrigation (AFI). Model calibration indicated contrasting controls on carbon and water exchanges between the two sites. At FR-Lam, relatively higher cuticular conductance and stronger atmospheric control on stomatal behaviour were identified, whereas at Ind-IITH, mesophyll conductance and soil moisture stress thresholds were important calibration parameters. At FR-Lam, the model simulated mean seasonal cumulative GPP, ET, and WUE of 1039 ± 20 gC m^{-2}, 610 ± 31 kg H_2O m^{-2}, and 1.70 ± 0.10 gC kg^{-1} H_2O, respectively, compared with measured values of 1026 ± 30 gC m^{-2}, 562 ± 42 kg H_2O m^{-2}, and 1.82 ± 0.11 gC kg^{-1} H_2O. At Ind-IITH, simulated values were 766 ± 15 gC m^{-2}, 567 ± 30 kg H_2O m^{-2}, and 1.35 ± 0.11 gC kg^{-1} H_2O, compared with measured values of 793 ± 11 gC m^{-2}, 522 ± 20 kg H_2O m^{-2}, and 1.51 ± 0.12 gC kg^{-1} H_2O. Diagnostic analysis based on underlying water use efficiency (uWUE) further indicated that the model reproduced the relationship between carbon assimilation and transpiration-driven water loss. Overall, ISBA-A-g_s captured the seasonal dynamics of maize carbon and water exchanges across the two contrasting climates, although differences between simulated and measured ET and WUE remained. The results highlight the potential of process-based modelling to assess carbon-water coupling across diverse hydroclimatic conditions and provide insights into the physiological controls governing crop water use.

~~Water use efficiency (WUE), a key ecohydrological indicator linking carbon assimilation and vegetation water loss, is critical for understanding ecosystem responses under changing hydro-climatic conditions. Process-based land surface models (LSMs) are widely used to represent carbon-water interactions; however, their ability to simulate ecosystem-scale WUE across contrasting climates remains limited. This study evaluates the performance of the Interactions~~

between Soil-Biosphere-Atmosphere model with A-g_s photosynthesis scheme (ISBA-A-g_s) implemented within the SURFEX land surface modelling platform in simulating gross primary productivity (GPP), evapotranspiration (ET), and WUE (GPP/ET) for maize grown under temperate (France, FR-Lam) and tropical semi-arid (India, Ind-IITH) climates. The model was driven by site-specific meteorological and vegetation variables across six growing seasons under sprinkler irrigation at FR-Lam, and two seasons (monsoon and winter) under alternate furrow irrigation (AFI) at Ind-IITH. Model calibration revealed that FR-Lam is characterized by relatively higher cuticular conductance and pronounced atmospheric control on stomatal behaviour, whereas at Ind-IITH, AFI induced adjustments in mesophyll conductance and soil moisture stress thresholds. At FR-Lam, ISBA-A-g_s simulated the seasonal mean cumulative GPP, ET, and WUE of 1039 ± 20 gC m^{-2}, 610 ± 31 kg H_2O m^{-2}, and 1.70 ± 0.10 gC kg^{-1} H_2O, respectively, as compared to measured values of 1026 ± 30 gC m^{-2}, 562 ± 42 kg H_2O m^{-2}, and 1.82 ± 0.11 gC kg^{-1} H_2O correspondingly. At Ind-IITH, the model simulated the seasonal mean cumulative GPP, ET, and WUE of 766 ± 15 gC m^{-2}, 567 ± 30 kg H_2O m^{-2}, and 1.35 ± 0.11 gC kg^{-1} H_2O, respectively, as compared to measured values of 793 ± 11 gC m^{-2}, 522 ± 20 kg H_2O m^{-2}, and 1.51 ± 0.12 gC kg^{-1} H_2O correspondingly. Further, the diagnostic analysis using the GPP·$VPD^{0.5}$-ET relationship revealed that ISBA-A-g_s realistically captures the coupling between carbon assimilation and transpiration driven water loss. Overall, ISBA-A-g_s demonstrates strong capability in simulating carbon and water fluxes of maize, particularly in representing WUE dynamics under contrasting climate regimes.

Keywords: Ecosystem modelling, Gross primary productivity, Evapotranspiration, Water use efficiency, Maize, Climate.

Research Highlights:

1. Multi-energy balance ISBA-A-g_s was applied to simulate maize WUE across temperate and tropical semi-arid climates.
2. Parameter calibration improved GPP simulations more substantially than ET.
3. The model reproduces irrigation-driven divergence in tropical semi-arid conditions, reflecting robust soil moisture stress and canopy resistance parameterization.
4. ISBA-A-g_s successfully reproduces the realistic coupling between photosynthesis and transpiration, as revealed by the underlying water use efficiency (uWUE) framework.
4.5. ~~ISBA-A-g_s successfully reproduces the GPP·VPD$^{0.5}$ ET relationship, indicating a realistic representation of photosynthesis-transpiration coupling~~.

1.0 Introduction

Water use efficiency (WUE) links carbon assimilation and water loss and is widely used to assess terrestrial ecosystem functioning and carbon-water interactions (Chen et al., 2022; Ito and Inatomi, 2012; Yu et al., 2008). At the ecosystem scale, WUE is commonly defined as the ratio of gross primary productivity (GPP) to evapotranspiration (ET), providing an integrated measure of carbon uptake relative to water loss (Beer et al., 2009; Vadez et al., 2023). Eddy covariance (EC) measurements are widely used to quantify carbon and water exchanges across ecosystems through international networks such as FLUXNET, NEON, ICOS, and AmeriFlux (Aubinet et al., 1999; Baldocchi, 2014; Baldocchi et al., 2001; Pastorello et al., 2020; Reichstein et al., 2005). However, EC measurements are often challenged by their spatial representativeness, high installation and maintenance costs, and sensitivity to surface heterogeneity (Hoover et al., 2023). Land surface models (LSMs) offer a complementary tool by representing the coupled physical, hydrological, and physiological processes governing exchanges between vegetation, soil, and the atmosphere. As a class of soil vegetation atmosphere transfer (SVAT) models, LSMs simulate key processes such as photosynthesis,

evapotranspiration, canopy conductance, soil moisture dynamics, and surface energy balance (Calvet, 2000; Knorr and Heimann, 1995; Noilhan and Planton, 1989). They therefore provide a process-based framework for investigating carbon-water coupling across different environmental conditions.

The Interactions between Soil, Biosphere, and Atmosphere (ISBA) scheme, originally developed by Noilhan & Planton (1989), is implemented within the SURFEX modelling platform maintained by Meteo-France (Masson et al., 2013). The ISBA family includes different configurations to represent land surface exchanges. The classical formulation uses a composite soil-vegetation surface temperature, whereas the Multi-Energy Balance (MEB) configuration (ISBA-MEB) explicitly separates soil and vegetation energy budgets, allowing a more detailed representation of heterogeneous surface exchanges (Boone et al., 2017). ISBA-MEB has been evaluated across grasslands and croplands in France (Boone et al., 2017; Dare-Idowu et al., 2021), irrigated and rainfed grasslands in Spain (Martí et al., 2026) and olive orchards and wheat fields in Morocco (Aouade et al., 2020). However, the performance and transferability of ISBA-based approaches for simulating carbon-water exchanges remain insufficiently assessed across contrasting hydroclimatic conditions, particularly in tropical semi-arid regions. In these environments, high atmospheric demand, strong solar radiation, seasonal rainfall, and irrigation-driven soil moisture variability can strongly influence stomatal regulation, photosynthesis, and evapotranspiration.

Maize (*Zea mays L.*) is a major cereal crop cultivated across a wide range of climatic conditions and used for food, feed, and bioenergy (Erenstein et al., 2022; Tanumihardjo et al., 2020). Its carbon assimilation, water use, and productivity are strongly influenced by climate, soil moisture availability, and irrigation management. These controls differ substantially between temperate and tropical semi-arid agroecosystems. In temperate regions such as France, maize is generally grown during the summer under relatively consistent seasonal conditions.

In tropical semi-arid regions of India, maize may be cultivated during both the monsoon and winter seasons, with rainfed and irrigated production systems experiencing high atmospheric demand and pronounced variations in water availability. These contrasting conditions provide an opportunity to examine how climate and water management influence carbon-water coupling. Despite the extensive cultivation of maize in both regions, long-term field observations of ecosystem carbon and water fluxes remain limited, particularly in semi-arid agricultural systems (Scott et al., 2023). Evaluating LSM performance across these contrasting environments is therefore important for identifying the strengths and limitations of model parameterizations and assessing their transferability under different climatic and water management conditions.

France and India provide contrasting examples of maize production and irrigation practices. In France, maize covers approximately 1.52 million hectares and accounts for nearly 17% of cereal production, with irrigation representing a substantial share of agricultural water use (Battude et al., 2017). In India, maize is cultivated over more than 9 million hectares and contributes approximately 10% of global production. Reported maize WUE values are around 3.5 gC Kg^{-1} H_2O in France and 1.83 gC Kg^{-1} H_2O in India, compared with a global average of approximately 4-5 gC Kg^{-1} H_2O (FAO, 2017; Sharma et al., 2018). Irrigation practices also differ between the two regions. French maize is commonly irrigated using sprinkler systems, whereas furrow irrigation is widely practised in India. Conventional furrow irrigation can lead to uneven soil wetting, increased soil evaporation, and deep percolation, potentially reducing WUE. Alternative strategies, including regulated deficit irrigation, conservation tillage, and alternate furrow irrigation (AFI), have been investigated to improve water productivity while maintaining crop yields (Al-Kayssi, 2023; Li et al., 2007; Yang et al., 2012). AFI alternates irrigation between adjacent furrows, modifying soil moisture distribution and root water uptake while potentially reducing irrigation inputs without substantial yield penalties (Chintala and

Kambhammettu, 2026; Kang et al., 1998, 2001). These changes can also affect stomatal regulation, transpiration, and carbon assimilation. However, their combined effects on ecosystem-scale carbon and water exchanges remain insufficiently quantified, particularly under semi-arid conditions.

Understanding these responses requires a model that represents the interactions among soil moisture, atmospheric demand, stomatal conductance, photosynthesis, and evapotranspiration. The ISBA-A-g_s model incorporates a photosynthesis-based stomatal conductance scheme, allowing carbon assimilation and transpiration to respond dynamically to environmental conditions (Calvet, 2000). Nevertheless, stomatal regulation involves complex physiological responses to radiation, vapour pressure deficit (VPD), and soil water availability that cannot be fully described by physical conservation laws alone (Buckley, 2017; Cowan and GD, 1977; Medlyn et al., 2011). Evaluating the model's ability to reproduce these responses is therefore essential for understanding its representation of carbon-water coupling. In addition to conventional WUE, underlying water use efficiency (uWUE) provides a complementary diagnostic by normalizing GPP with the square root of VPD. This formulation accounts for the theoretically predicted inverse square-root dependence of stomatal conductance on VPD under optimal stomatal regulation (Zhou et al., 2014). By reducing the first-order influence of atmospheric demand, uWUE can help assess the consistency of modelled carbon-water relationships and distinguish physiological responses from variations driven primarily by atmospheric conditions.

A systematic survey of the Scopus database covering 2004-2024, using the keywords "*ecosystem modelling*", *"modelling GPP and ET"*, *"modelling WUE"*, and *"land surface modelling on WUE"* identified a limited number of studies addressing the simultaneous modelling of carbon and water exchanges. The survey returned only four studies on GPP modelling and ten on ET modelling, with no identified study examining ecosystem-scale WUE

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using a locally calibrated LSM across contrasting climatic regimes. The modelling of WUE under contrasting irrigation treatments, particularly in semi-arid Indian agroecosystems, also remains poorly investigated. Addressing these gaps is important for evaluating the capacity of process-based models to represent carbon-water interactions under different climatic conditions and irrigation strategies. This study aims to evaluate and apply the ISBA-A-g_s land surface model to investigate maize carbon-water coupling across temperate conditions in France and tropical semi-arid conditions in India. Specifically, the objectives are to: (i) characterize the seasonal dynamics of GPP, ET, and WUE in maize under contrasting climatic conditions and irrigation treatments; (ii) calibrate and validate ISBA-A-g_s using site-specific parameterizations; (iii) simulate GPP, ET, and WUE using the calibrated model across the study sites; and (iv) diagnose the model's ability to reproduce the eco-physiological mechanisms governing carbon-water coupling, including the responses to atmospheric demand. Using comprehensive field measurements of carbon and water fluxes, this study provides a cross-climatic assessment of model performance and explores the influence of irrigation management on maize carbon assimilation and water use.

~~Water use efficiency (WUE) is a key ecohydrological indicator that deals with carbon and water cycles in terrestrial ecosystems (Chen et al., 2022; Ito and Inatomi, 2012; Yu et al., 2008). By linking carbon assimilation (as a proxy for photosynthesis) with vegetation water loss (as a proxy of evapotranspiration), WUE provides an integrated measure of ecosystem functioning at the land-atmosphere interface (Beer et al., 2009; Xue et al., 2015). At the ecosystem scale, WUE is typically defined as the ratio of gross primary productivity (GPP) to evapotranspiration (ET) over a relatively homogeneous surface (Beer et al., 2009; Vadez et al., 2023). In essence, it quantifies how efficiently agro-ecosystems convert available water into biomass through photosynthesis, with higher WUE indicating greater carbon gain per unit of water consumed. Micrometeorological approaches, particularly the eddy covariance (EC) setups, are now widely~~

used through international networks (FLUXNET, NEON, ICOS, AMERIFLUX) to directly measure surface-atmosphere exchanges of carbon and water fluxes at the ecosystem scale (Aubinet et al., 1999; Baldocchi, 2014; Baldocchi et al., 2001; Pastorello et al., 2020; Reichstein et al., 2005). Despite their robustness, EC measurements are constrained by limited spatial representativeness, high installation and maintenance costs, and sensitivity to surface heterogeneity (Hoover et al., 2023). For instance, models that accurately represent carbon and/or water fluxes are essential for understanding ecosystem responses to changing environmental conditions. Such models not only reproduce surface flux dynamics but also enable diagnostic analyses to assess ecosystem sensitivity to water stress, irrigation management, and climate variability. Approaches for estimating carbon and/or water exchanges can be broadly categorized into four groups: (i) remote sensing-based methods that infer productivity and evapotranspiration from satellite observations (Goetz et al., 2009; Potter et al., 2003), (ii) data-driven or empirical approaches relying on statistical relationships between fluxes and environmental drivers (Papale and Valentini, 2003), (iii) traditional crop growth models, which primarily focus on biomass accumulation under prescribed management conditions based on simplified numerical approaches (Moharana et al., 2025), and (iv) process-based Surface-Vegetation-Atmospheric Transfer (SVAT) models that represent physiological and biogeochemical mechanisms (Knorr and Heimann, 1995) including land surface models (LSMs) that explicitly couple biophysical, hydrological, and physiological processes within a physically consistent SVAT framework (Calvet, 2000; Noilhan and Planton, 1989). Among these, LSMs originally developed to represent land-atmosphere exchanges for numerical weather/climate prediction explicitly resolve energy balance, soil moisture variability, canopy resistance, and photosynthesis-transpiration interactions (Koster and Suarez, 1996; Liang et al., 1994). By incorporating local meteorological and vegetation characteristics, LSMs

dynamically provide a relevant platform for investigating ecosystem-scale GPP, ET, and further WUE dynamics under contrasting hydroclimatic regimes.

The Interactions between Soil, Biosphere, and Atmosphere (ISBA) scheme is a one such SVAT model originally developed by (Noilhan and Planton, 1989) and implemented within the SURFEX land surface modelling platform developed and maintained by Meteo-France, the French Weather Forecast Institute (Masson et al., 2013). ISBA provides the land surface boundary conditions (energy, water, and carbon fluxes) required by atmospheric models for numerical weather prediction and climate simulations (Noilhan and Planton, 1989). In its classical formulation, ISBA solves a single composite soil-vegetation surface temperature, which limits the representation of heterogeneous canopy-soil thermal exchanges (Noilhan and Planton, 1989). To overcome this limitation, (Boone et al., 2017) introduced a Multi-Energy Balance (MEB) version, hereafter referred to as ISBA-MEB. The MEB configuration explicitly separates soil and vegetation energy budgets, allowing up to three distinct source temperatures and flux pathways. The ISBA-MEB framework has been extensively evaluated over grasslands and croplands, within the temperate climate of France (Boone et al., 2017; Dare-Idowu et al., 2021), irrigated and rainfed grasslands in Spain (Martí et al., 2026) and Olive orchards and wheat in Morocco (Aouade et al., 2020). However, its performance remains largely unexplored outside temperate climates, especially under tropical semi-arid conditions, where high vapor pressure deficit, strong radiation loads, episodic monsoon rainfall, and irrigation-induced soil moisture heterogeneity exert strong controls on carbon-water coupling.

Maize (*Zea mays L.*) is one of the most widely cultivated cereal crops globally (15% of cultivated area) and serves as a staple food, feed, and bioenergy source, contributing substantially to global food security (Erenstein et al., 2022; Tanumihardjo et al., 2020). Gross primary productivity of maize typically ranges between 1500-2000 gC m^{-2} per growing season, depending on climate, management, and cultivar, with higher values observed under well-

managed, irrigated systems (Beer et al., 2010; Suyker and Verma, 2012). Evapotranspiration generally varies from 400–800 kg H_2O m^{-2}, reflecting differences in atmospheric demand, soil moisture availability, and irrigation regimes (Stoy et al., 2019; Suyker and Verma, 2009). Consequently, WUE for maize falls within 2.5–5.0 gC kg^{-1} H_2O, with irrigated and moderately water-limited systems often showing enhanced WUE due to optimized stomatal regulation. However, under water stress conditions, reductions in carbon assimilation typically outweigh declines in ET, leading to decrease in WUE. Extensive EC observations allow thorough assessments of maize GPP, ET, and WUE under a wide range of pedo-climatic conditions. These evaluations are essential not only for enhancing crop physiological understanding, but also promotes sustainable water and carbon management in maize agro-ecosystems.

For instance, models that accurately represent carbon and/or water fluxes are essential for understanding ecosystem responses to changing environmental conditions. Such models not only reproduce surface flux dynamics but also enable diagnostic analyses to assess ecosystem sensitivity to water stress, irrigation management, and climate variability. Approaches for estimating carbon and/or water exchanges can be broadly categorized into four groups: (i) remote sensing-based methods that infer productivity and evapotranspiration from satellite observations (Goetz et al., 2009; Potter et al., 2003), (ii) data-driven or empirical approaches relying on statistical relationships between fluxes and environmental drivers (Papale and Valentini, 2003), (iii) traditional crop growth models, which primarily focus on biomass accumulation under prescribed management conditions based on simplified numerical approaches (Meharana et al., 2025), and (iv) process-based Surface-Vegetation-Atmospheric Transfer (SVAT) models that represent physiological and biogeochemical mechanisms (Knorr and Heimann, 1995) including land surface models (LSMs) that explicitly couple biophysical, hydrological, and physiological processes within a physically consistent SVAT framework (Calvet, 2000; Noilhan and Planton, 1989). Among these, LSMs originally developed to

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Temperate regions play a dominant role in global carbon-water exchanges; however, cropping systems in these regions differ substantially from those in tropical semi-arid climates (Beer et al., 2010; Jung et al., 2010; Nelson et al., 2020). In temperate regions, maize is typically cultivated during the summer season, resulting in a single growing cycle per year under relatively stable climatic conditions. In contrast, tropical semi-arid regions, particularly under monsoonal-dependent conditions, often support two maize growing seasons annually: a rainfed monsoon crop and an irrigated winter crop. These systems are characterized by high atmospheric demand, strong intra-seasonal rainfall variability, and frequent soil moisture limitations (Trenberth, 2011; Wang-Erlandsson et al., 2014). Additionally, irrigation practices introduce complex and non-linear interactions between soil moisture availability and atmospheric demand, which are not adequately represented in models primarily developed for temperate systems. Despite the extensive cultivation of maize in semi-arid regions, the temporal dynamics of carbon-water exchanges in these agro-ecosystems remain insufficiently understood due to limited long-term in-situ observations (Scott et al., 2023). Therefore, applying and evaluating LSMs across contrasting temperate and tropical semi-arid climates is essential to (i) test the robustness of model parameterizations governing carbon-water coupling, (ii) identify climate-specific sensitivities and structural limitations, and (iii) improve the transferability of calibrated parameters for regional-scale simulations. Such cross-climatic

assessments are particularly critical for enhancing confidence in LSM-based predictions of GPP, ET, and WUE under future climate variability and irrigation adaptation scenarios.

The Interactions between Soil, Biosphere, and Atmosphere (ISBA) scheme is a one such SVAT model originally developed by (Noilhan and Planton, 1989) and implemented within the SURFEX land surface modelling platform developed and maintained by Meteo-France, the French Weather Forecast Institute (Masson et al., 2013). ISBA provides the land surface boundary conditions (energy, water, and carbon fluxes) required by atmospheric models for numerical weather prediction and climate simulations (Noilhan and Planton, 1989). In its classical formulation, ISBA solves a single composite soil vegetation surface temperature, which limits the representation of heterogeneous canopy-soil thermal exchanges (Noilhan and Planton, 1989). To overcome this limitation, (Boone et al., 2017) introduced a Multi Energy Balance (MEB) version, hereafter referred to as ISBA-MEB. The MEB configuration explicitly separates soil and vegetation energy budgets, allowing up to three distinct source temperatures and flux pathways. The ISBA-MEB framework has been extensively evaluated over grasslands and croplands, within the temperate climate of France (Boone et al., 2017; Dare-Idowu et al., 2021), irrigated and rainfed grasslands in Spain (Martí et al., 2026) and Olive orchards and wheat in Morocco (Aouade et al., 2020). However, its performance remains largely unexplored outside temperate climates, especially under tropical semi-arid conditions, where high vapor pressure deficit, strong radiation loads, episodic monsoon rainfall, and irrigation-induced soil moisture heterogeneity exert strong controls on carbon-water coupling.

In France, maize accounts for nearly 17% of total cereal production with cultivation over 1.52 million hectares, while consuming approximately 70-80% of irrigation water (Battude et al., 2017). Maize is predominantly cultivated during the summer season (May-August), coinciding with peak atmospheric evaporative demand and reduced river flows, thereby exerting significant pressure on regional water resources. In contrast, India contributes nearly

10% of global maize production, with cultivation extending over 9 million hectares. Despite its extensive cultivation in both countries, the WUE of maize in both France (3.5 gC $Kg^{-1}H_2O$) and India (1.83 gC $Kg^{-1}H_2O$) remains below the global average (4.5 gC $Kg^{-1}H_2O$) (FAO, 2017; Sharma et al., 2018). In France, maize is predominantly cultivated under sprinkler irrigation systems, where water is applied from above the canopy as pressurized droplets. In contrast, maize cultivation in India has traditionally relied on continuous furrow irrigation (CFI), where water is conveyed through furrows and allowed to infiltrate laterally and vertically, leading to near-saturated conditions across the entire field. Under CFI, prolonged surface wetting and deep percolation often result in low WUE, with substantial non-productive losses through soil evaporation and drainage below the root zone. Recent precision and conservation-oriented irrigation strategies such as regulated deficit irrigation, conservation tillage, and alternate furrow irrigation (AFI) have emerged as promising approaches to enhance WUE while sustaining yields (Al-Kayssi, 2023; Li et al., 2007; Yang et al., 2012). Among these, AFI has demonstrated considerable potential in reducing total irrigation inputs without significant yield penalties (Kang et al., 1998, 2001). The AFI technique alternates wetting and drying of adjacent furrows, inducing controlled and moderate water stress that enhances stomatal regulation and improves WUE. As AFI fundamentally modifies soil moisture distribution, root water uptake patterns, and canopy physiological responses relative to CFI, its influence on coupled carbon-water exchanges remains insufficiently quantified. Therefore, a robust process-based modelling framework capable of explicitly resolving soil-plant-atmosphere interactions is essential to evaluate the eco-physiological implications of contrasting irrigation regimes across diverse hydroclimatic conditions. These irrigation-induced changes ultimately propagate through stomatal regulation, which governs both carbon assimilation and transpiration at the leaf and ecosystem scales. However, stomatal regulation is a complex biological process that cannot be fully constrained by fundamental physical

~~conservation laws alone (Buckley, 2017; Cowan and GD, 1977; Medlyn et al., 2011), and it dynamically responds to radiation, vapour pressure deficit (VPD), and soil moisture conditions. Consequently, process based diagnostics are required to rigorously evaluate model performance in capturing carbon-water coupling. As transpiration increases with atmospheric dryness, direct GPP-ET relationships may primarily reflect atmospheric demand rather than intrinsic physiological regulation. To address this, the underlying water use efficiency (uWUE) framework (Zhou et al., 2014) was adopted, wherein GPP was normalized by $VPD^{0.5}$ to account for the theoretically predicted inverse square root dependence of stomatal conductance on VPD derived from optimal stomatal theory. This normalization reduces the first order atmospheric demand effect on transpiration, thereby enabling a more physiologically meaningful assessment of intrinsic carbon-water coupling.~~

~~A systematic survey of the Scopus database (2004-2024) using keywords: "*ecosystem modelling*", *"modelling GPP and ET"*, *"modelling WUE"*, and *"land surface modelling on WUE"* revealed a clear research gap. Only a limited number of studies have addressed the modelling of GPP (4) and ET (10), while no study has examined ecosystem scale WUE using a locally calibrated land surface model under contrasting climatic regimes. Notably, no study has simultaneously quantified WUE under contrasting irrigation treatments, particularly in Indian semi arid agro ecosystems where irrigation strongly regulates carbon-water coupling. Specifically, this study is aimed to: (i) characterize the dynamics of GPP, ET, and WUE of maize across both climates (temperate: France; tropical semi arid: India), (ii) simulate these fluxes using the ISBA-A-g_s SVAT model with site specific calibration and validation, (iii) analyse model sensitivity to climate specific parameterization and its influence on model simulations, and (iv) perform diagnostic analyses to assess the model's ability to reproduce underlying eco physiological mechanisms governing WUE. To achieve these, comprehensive~~

~~field measurements of GPP, ET, and WUE were considered in maize cultivated under contrasting climatic conditions subjected to different irrigation treatments.~~

~~This paper is organised as follows: (i) description of experimental sites and data collection, (ii) land surface model implementation, (iii) model simulations and validation, and (iv) diagnostic analysis on model simulations.~~

2.0 Material and Methods

2.1 Experimental sites description

2.1.1 Lamasquere, France (FR-Lam)

The Lamasquere experimental site (FR-Lam; 43°50′05″ N, 1°24′19″ E; 180 m above mean sea level) covers a flat area of ~~approximately~~ 24 ha, surrounded on its west and south sides by forest and is located about 25 km southwest of Toulouse, France (Figure 1). ~~FR-Lam is a Class 1 ecosystem station within the Integrated Carbon Observation System (ICOS) network and is also part of the regional Spatial Observatory (OSR) project. The experimental field is situated along the Touch River and is characterized by a soil texture consisting of 54.3% clay, 33.7% loam, and 12% sand, rather homogeneous vertically up to 1m deep.~~ According to the Köppen-Geiger climate classification, FR-Lam is categorized as a temperate oceanic climate (Cfb) (Kottek et al., 2006). ~~Despite a mean annual precipitation of 642 mm and a mean annual air temperature of 16.2°C, precipitation is not evenly distributed throughout the year. In particular, summer periods can experience pronounced drought and heatwave conditions, leading to elevated VPD (~ 0.60 to 0.72 kPa) and reduced soil moisture availability.~~ The regional wind regime is dominated by westerly and south-easterly winds, with an average wind speed of ~~about~~ 1.8 m s^{-1}. The site follows a regular 2-year crop rotation with wheat in the first year and intermediate cover followed by maize (summer crop) in the second year. Therefore, only years cultivated with maize were selected for this study (2006, 2008, 2010, 2012, 2014,

and 2015). Summer maize (silage) is generally sown between April and May, irrigated during the mid-season, and harvested from late August to early September. ~~A shift in cultivar occurred during the 2014 and 2015 maize growing seasons.~~ Pivot irrigation was applied during 2008 and 2010, whereas sprinkler irrigation was adopted in the remaining years. Details of the crop cycles and associated biophysical variables for the selected seasons are provided in Table 1.

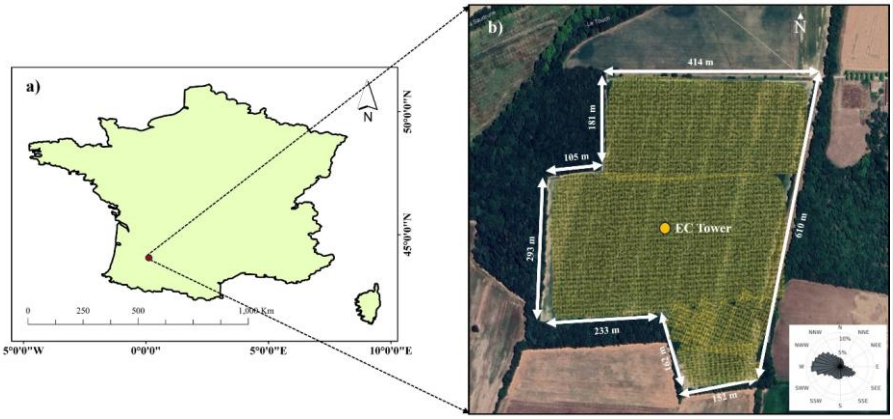


Figure 1. Overview of the FR-Lam experimental site: **(a)** Location of the study site; **(b)** Field extent and position of the EC tower within the site (Inset: observed wind rose diagram). Map source: The base map was designed and developed by Esri | Powered by Esri.

Table 1. Maize crop cycles with total rainfall and irrigation, sowing and harvest dates, crop length and maximum leaf area index (LAI) at FR-Lam experimental site.

Crop season	Rain [mm]	Irrigation [mm]	Total water [mm]	Sowing Date [DD/MM/YYYY]	Harvest Date [DD/MM/YYYY]	Crop length [Days]	Max LAI [m^2 m^{-2}]	Atmospheric evaporative demand ET_o [mm]
2006	265.5	45.25	310.75	01/05/2006	31/08/2006	123	3.1	403
2008	269.67	27.30	296.97	20/05/2008	11/09/2008	124	3.8	363

2010	196.61	106.10	302.61	21/04/2010	20/09/2010	138	4.0	432
2012	410.07	148.70	558.07	27/04/2012	23/08/2012	122	5.8	374
2014	331.05	167.70	498.05	14/05/2014	22/09/2014	131	5.2	388
2015	354.41	120.00	474.41	05/05/2015	08/09/2015	128	6.6	435

Monthly variations in major meteorological variables in Figure 2 shows that, 2008 received the lowest rainfall (270 mm), whereas 2012 recorded the highest (410 mm), corresponding to distinctly dry and wet years, respectively. Supplemental irrigation was primarily required during July and August (393 mm), coinciding with the peak vegetative growth stage (dough) for all the years. The balance between total available water (precipitation + irrigation) and atmospheric evaporative demand (ET_o) further highlighted interannual contrasts, with positive (+184 mm) and negative (-66 mm) water surpluses observed during 2012 and 2008, respectively. Seasonal mean air temperature ranged from 17 ± 1.60°C in 2012 to 19.50 ± 1.20°C in 2008, consistent with rainfall-driven wet and dry classifications. Similarly, mean VPD varied from 0.67 ± 0.10 kPa in 2012 to 0.78 ± 0.10 kPa in 2008, indicating greater atmospheric water demand in dry seasons. LAI displayed strong seasonal variability, with lower values observed in 2006 (3.1 m^2 m^{-2}), 2008 (3.9 m^2 m^{-2}), and 2010 (4 m^2 m^{-2}) compared to later years (2012: 5.9 m^2 m^{-2}; 2014: 5.2 m^2 m^{-2}; 2015: 6.6 m^2 m^{-2}). Overall, the FR-Lam site exhibited pronounced seasonal and interannual variability, with relatively drier conditions during the early seasons (2006, 2008, and 2010) and wetter conditions in later years (2012, 2014, and 2015). In addition to climatic variability, a change in maize cultivar during 2014 and 2015 contributed to improved canopy development and higher yield, indicating that both environmental conditions and management practices influenced crop performance.

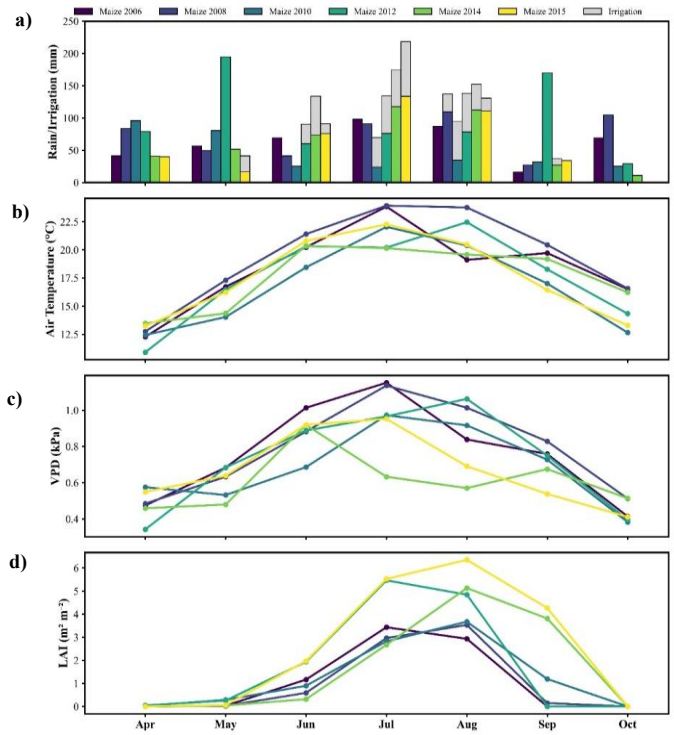


Figure 2. Monthly variations in environmental variables, including rainfall/Irrigation (cumulative values) **(a)**; Air temperature **(b)**; Vapor pressure deficit **(c)**; and Leaf area index **(d)** observed at FR-Lam experimental site during maize growing seasons.

2.1.2 Hyderabad, India (Ind-IITH)

Field experiments were conducted at the Ind-IITH site (17°35′48.44″ N, 78°07′05.78″ E; 549 m above mean sea level) in two adjacent agricultural fields located ~~approximately~~ nearly 2 km from the Indian Institute of Technology Hyderabad (IITH), Telangana, India (Figure ~~2~~3). Each field measures 100 m in length × 62 m in width, covering an area of about 0.62 ha. According to the Köppen-Geiger climate classification, the region falls under a tropical savannah climate (Aw), characterized by long dry periods and a short, intense wet season (Kottek et al., 2006). ~~The soil at the experimental site consists of 10% clay, 15% loam, and~~

~~60% sand, exhibiting vertical homogeneity up to 1m deep.~~ ~~Mean annual precipitation ranges from 880 to 920 mm, with approximately 70% of the rainfall occurring during the southwest monsoon period (June-September). The average daily air temperature varies between 32 to 40°C during summer (April-June) and 22 to 24°C during winter (December-February), while VPD ranges from 1.11 kPa in summer to 2.72 kPa in winter.~~ The regional wind regime is dominated by strong easterly winds, with a mean wind speed of about ~~approximately~~ 1.05 m s^{-1}. Cropping patterns in the region are largely confined to two seasons, namely: the monsoon (kharif) and winter (rabi). During the monsoon season, maize is typically sown in mid-June and harvested by early October, whereas winter maize is sown in early December and harvested by early April. Two irrigation treatments, continuous furrow irrigation (CFI) and alternate furrow irrigation (AFI), were implemented, with irrigation water applied uniformly to all furrows under CFI and alternated between furrows based on the prevailing soil moisture conditions under AFI. ~~Two EC towers considering irrigation treatments: one for alternate furrow irrigation (AFI) and another for continuous furrow irrigation (CFI) were installed each field. Under CFI, irrigation water is applied uniformly to all furrows, while under AFI, irrigation alternates between furrows based on the prevailing soil moisture conditions.~~ Details of the crop cycles and associated biophysical variables for the selected seasons are summarized in Table 2.

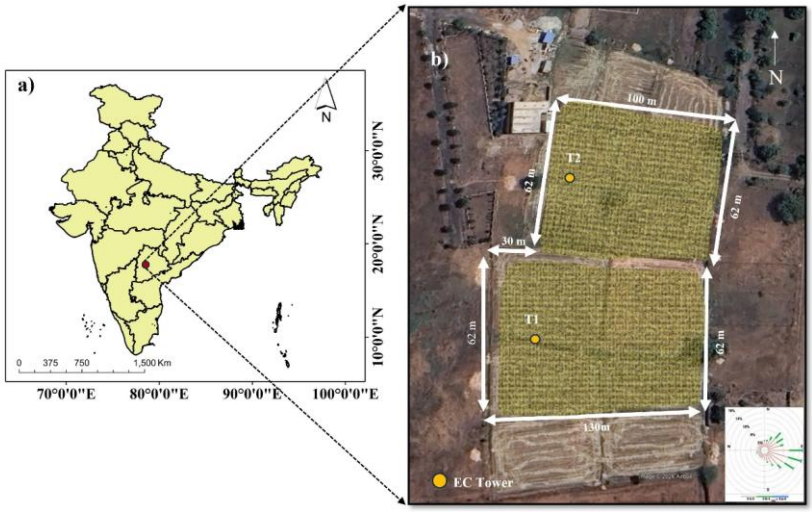


Figure 23. Overview of the Ind-IITH experimental site: **(a)** Location of the study site; **(b)** Field extent and position of the EC towers within the site (Inset: Observed Windrose diagram). Map source: The base map was designed and developed by Esri | Powered by Esri.

Table 2. Maize crop seasons with irrigation method, total rainfall and irrigation, sowing and harvest dates, crop length and maximum leaf area index (LAI) at Ind-IITH experimental site.

Crop season	Irrigation method	Rain [mm]	Irrigation [mm]	Sowing Date [DD/MM/YYYY]	Harvest Date [DD/MM/YYYY]	Crop length [Days]	Max LAI [m^2 m^{-2}]	Atmospheric evaporative demand ET_o [mm]
Monsoon	CFI	509	47	22/06/2024	05/10/2024	110	2.4	620
Monsoon	AFI	509	42	22/06/2024	05/10/2024	110	2.3	620

Winter	CFI	0	353.4	25/11/2024	10/04/2025	136	3.5	705
Winter	AFI	0	353.4	25/11/2024	10/04/2025	136	3.4	705

Variations in major meteorological variables in Figure 4 shows that, rainfall was predominantly concentrated during the monsoon season (June-August), totalling 509 mm, while three irrigation events, totalling 46.8 mm, were applied primarily during the dough (grain-filling) and maturity stages. Despite this additional input, the balance between total available water (precipitation/irrigation) and atmospheric evaporative demand (ET_o) remained negative, with deficits of -64 mm and -81 mm under CFI and AFI treatments, respectively. In contrast, the winter season received no rainfall, making the crop entirely dependent on irrigation, with total irrigation amounts of 543 mm under CFI and 453 mm under AFI. Despite these irrigation inputs, total available water remained below the ET_o, resulting in water deficits of -163 mm under CFI and -252 mm under AFI. Air temperature remained relatively stable during the monsoon (28.23 ± 1.20 °C), whereas during the winter season it increased progressively from 25.63 °C to a peak of 38.63 °C toward the end of the growing season. VPD variations closely followed temperature patterns, with mean values of 1.12 kPa and 2.73 kPa during the monsoon and winter seasons, respectively. Average LAI was lower during the monsoon (1.33 m^2 m^{-2}) compared to winter (1.97 m^2 m^{-2}), likely influenced by seasonal differences in radiation and atmospheric conditions. Overall, the monsoon period exhibited relatively stable temperatures and lower VPD, whereas the winter season experienced progressively increasing temperatures and substantially higher VPD, indicating greater atmospheric water demand. Overall, the FR-Lam showed moderate year-to-year differences in climate, whereas Ind-IITH exhibited a near-complete shift from water-abundant to water-deficient conditions between two seasons, along with a marked increase in VPD.

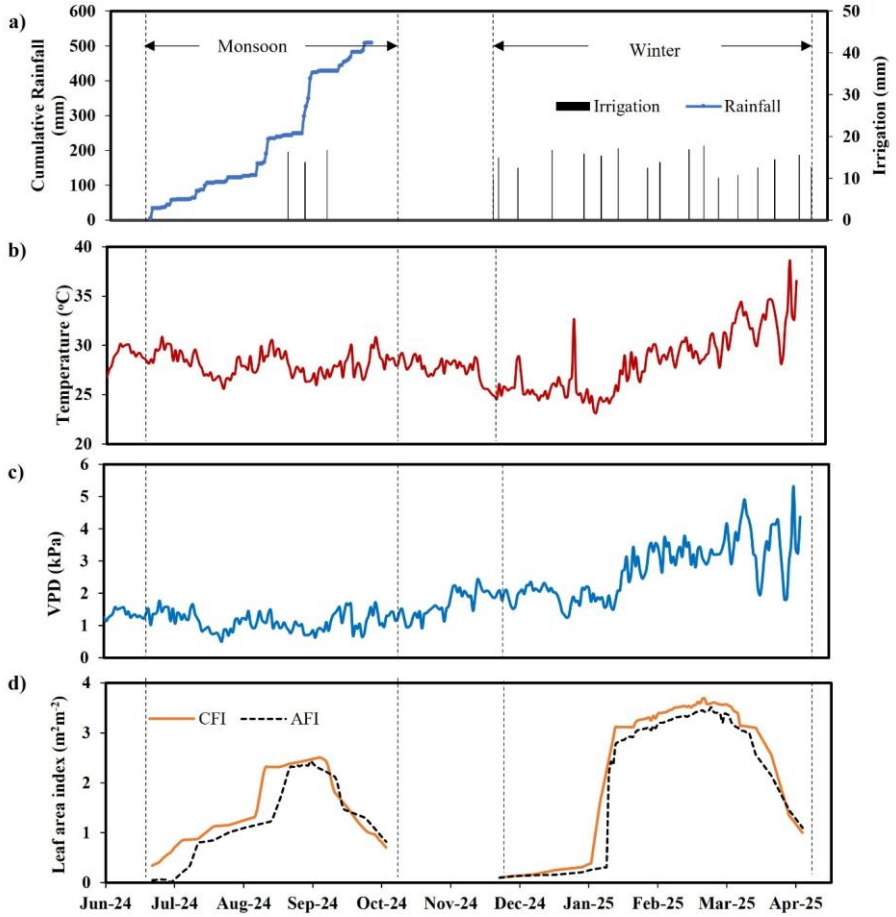


Figure 4. Seasonal variations in environmental variables, including cumulative rainfall and Irrigation **(a)**; Air temperature **(b)**; Vapor pressure deficit **(c)**; Leaf area index **(d)** observed at Ind-IITH experimental site during maize growing seasons.

~~A comparative analysis of meteorological conditions between the FR-Lam and Ind-IITH sites reveals that the climate variability at the FR-Lam site was primarily expressed between years, distinguishing relatively dry (e.g., 2008) and wet (e.g., 2012) seasons, while maintaining a consistent growing period from April to September with moderate fluctuations~~

~~in rainfall and VPD. In contrast, the Ind-IITH site exhibited pronounced intra-annual variability, with a sharp transition between monsoon and winter seasons. Rainfall was concentrated during the monsoon, whereas winter conditions were entirely irrigation-driven, resulting in contrasting water availability regimes. These seasonal differences were further amplified by atmospheric demand, with substantially higher VPD observed during winter compared to the relatively stable monsoon period. Importantly, the seasonal contrasts at Ind-IITH exceeded the interannual variability observed at FR-Lam, particularly in cumulative rainfall and VPD. While FR-Lam showed moderate year-to-year differences in precipitation, Ind-IITH exhibited a near-complete shift from water-abundant to water-deficient conditions between seasons, along with a marked increase in VPD. These differences were also reflected in canopy development, where LAI variability at FR-Lam was linked to both climatic conditions and management factors (e.g., sowing date and cultivar change), whereas at Ind-IITH, LAI differences were mainly driven by seasonal contrasts in radiation, temperature, and water availability. Overall, climatic variability at Ind-IITH is substantially greater at the seasonal scale, especially for VPD and water inputs, with important implications for crop water use and WUE dynamics.~~

2.2 Field measurements

2.2.1 Eddy c~~C~~ovariance and ~~M~~meteorological ~~D~~datasets

At the FR-Lam site, an eddy covariance (EC) system was installed at 3.65m above ground level. The system comprised a three-dimensional sonic anemometer (CSAT-3; Campbell Scientific Inc., USA) and an open-path infrared gas analyser (LI-7500; LI-COR Inc., USA). Turbulent fluxes of CO_2 and H_2O were measured at 20 Hz using a datalogger (CR3000; Campbell Scientific Inc., USA) and subsequently averaged over a 30-minute interval. High-frequency raw data were processed using the EdiRe software following the CarboEurope-IP

protocol (Aubinet et al., 1999) and the FLUXNET2015 processing guidelines (Pastorello et al., 2020). After standard quality control procedures, net ecosystem exchange (NEE) was calculated as the sum of turbulent CO_2 flux and the CO_2 storage ~~term~~ within the canopy. NEE was further partitioned into ecosystem respiration (R_{eco}) and gross primary productivity (GPP) using the method proposed by ~~(~~Reichstein et al.~~,~~ (2005). This partitioning method had been optimized for croplands by ~~(~~Béziat et al.~~,~~ (2010) (see also (Pique et al., 2020) for further details). Flux footprint estimates were derived using the analytical model of ~~(~~Kljun et al.~~,~~ (2004). Meteorological variables, including net radiation (CNR1; Kipp & Zonen), wind speed and wind direction (wind vane/propeller; R.M. Young), air temperature and relative humidity (HMP35; Vaisala), precipitation (ARG100 rain gauge), and diffuse and total photosynthetic active radiation (PAR) (BF3; Delta-T Devices Ltd., Cambridge, UK), were measured at a half-hourly interval. ~~Ground heat flux was measured at a depth of 5cm using heat flux plates (HFP01; Hukseflux Thermal Sensors B.V., the Netherlands) and calculated as the average of four sensors installed around the EC tower. The soil heat storage was computed using the soil texture and soil water content to provide the total soil heat flux at the surface.~~ The quality of the convective fluxes measured by the EC system was evaluated by estimating energy balance closure (see (Dare-Idowu et al., 2021)). Data points exhibiting poor closure (< 0.3) were excluded from the dataset to ensure the reliability of the flux measurements (Barr et al., 2006; Kidston et al., 2010). On average, 48% of the nighttime data was rejected due to insufficient turbulence. ~~Soil temperature and volumetric soil water content were monitored at depths of 0, 5, 10, 30, 50, and 100 cm below soil surface. Measurements were performed using time-domain reflectometry probes (CS616; Campbell Scientific Inc., USA) from 2005 to 2011 and using Thetaprobe sensors (ML2X; Delta-T Devices Ltd., UK) from 2012 to 2015, with four replicated profiles distributed around the mast.~~ A detailed description of the experimental setup and instrumentation is provided in ~~(~~Béziat et al.~~,~~ (2010) and~~,~~ Dare-Idowu et al.~~,~~ (2021).

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At the Ind-IITH site, both experimental fields were equipped with open-path eddy covariance (EC) flux towers installed at a height of 2.2m above ground level. The EC system consisted of an open-path infrared gas analyser (IRGASON-EB-NC; Campbell Scientific Inc., USA) coupled with a 3D sonic anemometer (EC100; Campbell Scientific Inc., USA) for continuous measurements of CO_2 and H_2O fluxes. High-frequency raw data were recorded at 10 Hz using dataloggers (CR3000 and CR1000X; Campbell Scientific Inc., USA) and subsequently averaged to a 30-minute interval. Raw EC data were processed using EasyFlux-PC software (Campbell Scientific Inc., USA). Detailed descriptions of data processing steps, quality control procedures, and flux corrections are provided in ~~(~~Karimindla et al.~~,~~ (2024). Gap filling of missing flux data was performed using the 'REddyProc' package in the open-source 'R' environment, following the method proposed by ~~(~~Reichstein et al.~~,~~ (2005). Net ecosystem exchange (NEE) was calculated as the sum of turbulent CO_2 fluxes and the CO_2 storage ~~term~~ within the canopy. NEE was further partitioned into ecosystem respiration (R_{eco}) and gross primary productivity (GPP) using the nighttime-based partitioning approach of ~~(~~Reichstein et al.~~,~~ (2005). Flux footprint estimates were derived using the analytical model developed by ~~(~~Kljun et al.~~,~~ (2004). Meteorological variables, including net radiation (CNR4; Campbell Scientific Inc., USA), air temperature and relative humidity (CS215 probe), wind speed and wind direction (propeller wind monitor; R.M. Young), and precipitation (TE525-L rain gauge; Campbell Scientific Inc., USA), were measured at 30-minute intervals~~. Soil heat flux (G) was measured using soil heat flux plates (HFP01SCL-PTL; Campbell Scientific Inc., USA) installed at a depth of 5 cm below the soil surface.~~ Similar to FR-Lam, datapoints exhibiting poor closure (< 0.3) were excluded from the dataset to ensure the reliability of the flux measurements (Barr et al., 2006; Karimindla et al., 2024; Kidston et al., 2010). ~~Soil volumetric water content and soil temperature at depths of 5, 10, and 30 cm were monitored using~~

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~~frequency-domain reflectometry sensors (TEROS-10; METER Group, USA) installed adjacent to the EC tower.~~

2.2.2 Vegetation characteristics and ~~i~~Irrigation inputs

At the FR-Lam site, vegetation leaf area index (LAI) was monitored during the peak growth period using a leaf area meter (LI-3100; LI-COR, Lincoln, NE, USA), following the methodology described by ~~(~~Claverie et al.~~,~~ (2012). In addition, vegetation height (h_{veg}) and aboveground biomass were measured on site from field sub-sampling and compared to the yield provided by the farmer. Information on irrigation timing and applied water amounts was collected through regular farmer surveys. A comprehensive description of vegetation monitoring protocols and management practices is provided in ~~(~~Dare-Idowu et al.~~,~~ (2021) and ~~(~~Pique et al.~~,~~ (2020). At the Ind-IITH site, LAI was measured from the tasselling to harvest stages using a plant canopy analyser (LI-2200C; LI-COR, Lincoln, NE, USA). Vegetation height was measured manually using a graduated ruler. Aboveground biomass and grain yield were determined at harvest from field sampling. Irrigation timing and applied water amounts were recorded on a daily basis for both CFI and AFI treatments.

~~2.3~~ 2.3 ISBA-A-g_s model description and implementation ~~Land surface model description and implementation~~

~~2.3.1~~2.3 ~~ISBA-A-g_s model description~~

The standard version of ISBA represents land surface heterogeneity using nineteen generic land cover types or patches: bare soil, rocks, ice and permanent snow, needleleaf trees, evergreen broadleaf trees, deciduous broadleaf trees, C3 crops, C4 crops, irrigated crops, herbaceous vegetation, tropical herbaceous vegetation, and wetlands (Calvet et al., 1998; Noilhan and Planton, 1989). In this study, ISBA was applied at a field scale (for which the

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cover is assumed to be homogeneous), and a single grid cell is characterized by a single dominant surface type (Noilhan and Planton, 1989). ISBA is implemented within the open-source SURFace EXternalisée (SURFEX) platform (version 9.1), developed by the Centre National de Recherches Météorologiques (CNRM) at Météo-France (Masson et al., 2013). In its standard configuration, leaf stomatal conductance is parameterized using the empirical approach of ~~(~~Jarvis, ~~(~~1976), which relies on multiplicative stress functions. While computationally efficient, this formulation has limitations in explicitly representing the physiological coupling between photosynthesis and stomatal regulation and doesn't account for the direct effects of atmospheric CO_2 concentration on carbon assimilation and stomatal conductance. To overcome these limitations, ISBA was revised by ~~(~~Calvet et al.~~,~~ ~~(~~1998) through the incorporation of an optional photosynthesis-based stomatal conductance scheme, commonly referred to as the 'A-g_s' model, originally proposed by ~~(~~Jacobs et al.~~,~~ ~~(~~1996). ~~This revised formulation explicitly links stomatal conductance to leaf-level photosynthetic activity, allowing a more mechanistic representation of CO_2 assimilation and stomatal regulation, and thereby improving the representation of vegetation-atmosphere carbon and water exchanges.~~ In the Jacobs formulation, leaf-level carbon assimilation and stomatal conductance are simulated through a sequence of steps (described in Appendix A of ~~(~~Calvet et al.~~,~~ ~~(~~1998) and ~~;~~ Rivalland et al.~~,~~ ~~(~~2005)), with the net assimilation rate (A_m) and stomatal conductance (g_s) expressed as:

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$$A_m = A_{m,max}\left[1 - \exp\left(-\frac{g_m^*(C_i - \Gamma)}{A_{m,max}}\right)\right] \quad (1)$$

$$g_s = 1.6\, g_{sc} + g_c \quad (2)$$

where $A_{m,max}$(mg m^{-2} s^{-1}) is the maximum photosynthetic rate, Γ(µmol mol^{-1}) is the CO_2 compensation concentration, g_m^* (m s^{-1}) is the unstressed mesophyll conductance, C_i(µmol mol^{-1}) is the intercellular CO_2 concentration, g_s (m s^{-1}) is the stomatal conductance, g_{sc} (m s^{-1}) is the

stomatal conductance to carbon and g_c (m s^{-1}) is the cuticular conductance. Typical values of $A_{m,max}$ for C3 and C4 crops, data are provided in (Calvet, (2000).

Radiative transfer scheme is applied to upscale these carbon and water fluxes to the canopy scale, following the approaches of (Jacobs, (1994) and (Roujean, (1996). At the canopy level, gross primary productivity (GPP; g-C m^{-2} s^{-1}) and evapotranspiration (ET; kg H_2O m^{-2} s^{-1}) are simulated, and water use efficiency (WUE) is then computed as a ratio of GPP to ET on a daily scale:

$$\text{WUE (g-C kg } H_2O^{-1}) = \frac{\text{GPP}}{\text{ET}} \quad (3)$$

~~2.3.2 Model implementation~~

In this study, the non-interactive vegetation option of ISBA-A-g_s is employed, the key vegetation characteristics: ~~leaf area index (~~LAI~~)~~, vegetation height (h_{veg}), and fractional vegetation cover (F_C) are prescribed using *in situ* measurements rather than simulated dynamically. The multilayer soil diffusion (DIF) scheme is adopted to simulate vertical transfers of soil moisture and heat within the soil profile (Decharme et al., 2026). ~~Within the SURFEX framework, land surface parameters and ancillary variables are typically derived from the ECOCLIMAP II database (Faroux et al., 2013). However, as the present study focuses on ecosystem-scale simulations and benefits from detailed field observations, the default ECOCLIMAP II parameterization is bypassed, and site-specific in situ measurements are used to constrain the model configuration.~~ The main input parameters and state variables used in the model simulations for the FR-Lam and Ind-IITH sites are summarized in Tables 3 and 4, respectively. At both sites, vegetation characteristics including ~~leaf area index (~~LAI~~)~~, ~~canopy height (~~h_{veg}~~)~~, and ~~fractional vegetation cover (~~F_c~~)~~ were prescribed from in-situ measurements at 10-day intervals. Surface roughness length was estimated as a fixed fraction of canopy height ($0.15 \times h_{veg}$). In this study, patch 8, representing C4 crops, was employed to simulate the maize

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crop at both sites. The model was forced with half-hourly meteorological observations, including air temperature (TA, K), specific humidity (QA, kg kg^{-1}), surface air pressure (PS, Pa), incoming longwave radiation (LWin, W m^{-2}), wind speed (WS, m s^{-1}), wind direction (degrees), ambient CO_2 concentration (kg m^{-3}), rainfall (RAIN, kg m^{-2}), and incoming shortwave radiation (SWin, W m^{-2}). The multilayer soil diffusion scheme requires information on soil stratification; accordingly, eight soil layers were defined at depths of 0, 5, 10, 30, 50, 100, and 150 cm below the ground surface. Soil hydraulic conductivity was estimated using pedotransfer functions based on measured sand and clay contents at the respective depths (Cosby et al., 1984). Initial soil moisture and soil temperature profiles were prescribed using in-situ observations. Surface albedo during active sunshine hours (10:00-15:00 local time) is provided to minimize the influence of low solar zenith angles, following (Kalma and Stanhill, (1969). Subsequently, total surface albedo was partitioned into soil (alb_{soil}) and vegetation (alb_{veg}) components using a fractional weighting approach based on F_C. Model simulations were constrained to the crop growth period by prescribing site-specific sowing and harvesting dates in the forcing files.

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Table 3. Values and ranges of ISBA-A-g, model input variables considered at FR-Lam experimental site.

Description	Symbol	Range	Unit	Reference
Leaf area index	LAI	0-6.8	[m^2 m^{-2}]	Measured
Minimum Leaf Area Index	LAI_{Min}	0.1-0.4	[m^2 m^{-2}]	Measured
Vegetation Height	h_{veg}	0-3.3	[m]	Measured
Fractional vegetation cover	F_e	0-1.0	-	Estimated
Vegetation albedo	alb_{veg}	0.16-0.21	-	Derived from measurement

Soil albedo	alb_{soil}	0.12–0.16	-	Derived from measurement
Max solar radiation available for photosynthesis	R_{GL}	80–100	[W m^{-2}]	(Moigne and Boone, 2012)
Vegetation emissivity	$Emis_{veg}$	0.97	-	-
Soil albedo	$Emis_{soil}$	0.90	-	-
Clay fraction	Cl	0.54	-	Measured
Sand fraction	Sd	0.12	-	Measured
Mesophyll conductance	gm	0.001–0.03	[m s^{-1}]	(Calvet, 2000)
Minimum stomatal resistance	RSMIN	40	[s m^{-1}]	(Calvet, 2000)
Cuticular conductance	GC	0.00015—0.00030	[m s^{-1}]	(Gibelin et al., 2006)
Critical normalized soil water content for stress parameterization	F2I	0.2—0.5	-	(Calvet, 2000)
Ecosystem respiration parameter	RE25	0.0000002—0.0000003	[kg/kgms^{-1}]	(Gibelin et al., 2006)
Maximum leaf to air saturation deficit	D_{Max}	0.05—0.5	[kg kg^{-1}]	(Calvet, 2000)
Vegetation thermal inertia coefficient	C_V	0.00005	[K m^{-2} J^{-1}]	(Noilhan and Planton, 1989)
Coeff for max inter-water storage capacity	WR_{Max}	0.05—0.3	-	(Moigne and Boone, 2012)
Ratio of surface roughness lengths	Z_0-Z_H	7—10	-	(Boone et al., 2017)

Table 4. Values and ranges of ISBA-A-g$_s$-model input variables considered at Ind-IITH experimental site.

Description	Symbol	Range	Unit	Reference
Leaf area index	LAI	0-3.6	[$m^2 m^{-2}$]	Measured
Minimum Leaf Area Index	LAI_{Min}	0.1-0.4	[$m^2 m^{-2}$]	Measured
Vegetation Height	h_{veg}	0-2.71	[m]	Measured
Fractional vegetation cover	F_c	0-1.0	-	Estimated
Vegetation albedo	alb_{veg}	0.16-0.18	-	Derived from measurement
Soil albedo	alb_{soil}	0.12-0.15	-	Derived from measurement
Max solar radiation available for photosynthesis	R_{GL}	80-200	[$W m^{-2}$]	Derived from measurement
Vegetation emissivity	$Emis_{veg}$	0.96	-	-
Soil albedo	$Emis_{soil}$	0.90	-	-
Clay fraction	Cl	0.10	-	Measured
Sand fraction	Sd	0.60	-	Measured
Mesophyll conductance	gm	0.001-0.03	[$m s^{-1}$]	(Calvet, 2000)
Minimum stomatal resistance	RSMIN	37	[$s m^{-1}$]	(Calvet, 2000)
Cuticular conductance	GC	0.00015—0.00030	[$m s^{-1}$]	(Gibelin et al., 2006)
Critical normalized soil water content for stress parameterization	F2I	0.21—0.48	-	(Calvet, 2000)

~~Ecosystem respiration parameter~~	~~RE25~~	~~0.0000002 – 0.0000003~~	~~[kg/kgms^{-1}]~~	~~(Gibelin et al., 2006)~~
~~Max leaf to air saturation deficit~~	~~D_{Max}~~	~~0.05 – 0.45~~	~~[kg kg^{-1}]~~	~~(Calvet, 2000)~~
~~Vegetation thermal inertia coefficient~~	~~C_V~~	~~0.00005~~	~~[K m^2 J^{-1}]~~	~~(Noilhan and Planton, 1989)~~
~~Coeff for max inter water storage capacity~~	~~WR_{Max}~~	~~0.05 – 0.35~~	~~-~~	~~(Moigne and Boone, 2012)~~
~~Ratio of surface roughness lengths~~	~~Z_o-Z_H~~	~~7 – 10~~	~~-~~	~~(Boone et al., 2017)~~

2.4 Model calibration and validation

To achieve an optimal balance between the large number of input parameters in ISBA-A-g_s and the available computational resources, a stepwise calibration strategy was adopted. Based on previous studies and expert knowledge of the model, 12 parameters (gm, GC, F2I, RE25, D_{Max}, C_V, LAI_{Min}, R_{GL}, RSMIN, WR_{Max}, and Z_o-Z_H) that potentially influencing GPP and ET were initially selected (Aouade et al., 2020; Boone et al., 2017; Dare-Idowu et al., 2021). A one-at-a-time (OAT) sensitivity analysis was first performed by varying each parameter independently while keeping all other parameters fixed. For each parameter, 50 simulations were conducted across its predefined range for each calibration dataset. Model performance was evaluated by comparing simulated GPP, ET, and WUE against in-situ observations using the root mean square error (RMSE) and coefficient of determination (R^2). Parameter sensitivity was assessed using a Pareto-based multi-objective framework, with RMSE and R^2 as the objective functions (Demarty et al., 2005), followed by the Kolmogorov-Smirnov (KS) test to quantify the statistical separation between acceptable and non-acceptable parameter sets. The OAT sensitivity analysis was then used to identify the most influential

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parameters. No automated optimization algorithm was employed. Instead, the sensitive parameters were manually refined through an iterative trial-and-error procedure, in which parameter values were progressively adjusted within their physically realistic ranges. Model simulations were repeatedly evaluated until further improvements in RMSE and R^2 became negligible while maintaining physically realistic parameter values. For the FR-Lam site, calibration was performed using the 2008, 2010, and 2012 growing seasons, and the optimized parameter set was independently validated using the 2006, 2014, and 2015 growing seasons. At the Ind-IITH site, owing to the availability of only one year of observations (monsoon and winter seasons under CFI and AFI), treatment-specific parameter sets were calibrated separately for each irrigation treatment and season. Independent temporal validation was therefore not feasible for the Ind-IITH site, and model transferability across contrasting hydro-climatic conditions was evaluated primarily through comparison with the independently validated FR-Lam simulations.

~~A 'one-at-a-time' sensitivity analysis was then performed to isolate the effect of each parameter. Simulations were conducted for three maize growing seasons (2008, 2010, and 2012) at the FR-Lam site and for four treatments (2 seasons) at the Ind-IITH site. For each parameter, a realistic range was defined based on literature values, and 50 simulations were performed per parameter for each crop year. Model performance was evaluated by comparing simulated GPP, ET, and WUE fluxes with in-situ observations using the root mean square error (RMSE) and the coefficient of determination (R^2). The performance metrics were ranked by minimizing RMSE and maximizing R^2, and a Pareto-based multi-objective approach (Demarty et al., 2005) was used to partition simulations into acceptable and non-acceptable parameter sets. To quantify parameter sensitivity, the cumulative distributions of acceptable and non-acceptable parameter values were compared using the Kolmogorov–Smirnov (KS) test, which provides a probability value describing the statistical separation between the two distributions.~~

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~~The optimized parameter set was subsequently validated using independent crop years (FR-Lam: 2006, 2014, and 2015; Ind-IITH: two seasons) not included in the calibration phase.~~

2.5 Model assessment

Model performance in reproducing GPP, ET, and WUE was evaluated using three goodness-of-fit indicators. EC flux-tower measurements were used as the reference for model validation. The selected indicators quantify the strength of association, residual errors, and systematic bias between observations and simulations. These metrics were computed using paired EC-observed values (O_i) and ISBA-A-g_s simulated values (P_i) of GPP, ET, and WUE, along with their respective means ($\bar{O}$ and $\bar{P}$), during crop growth seasons. Model performance was assessed using the coefficient of determination (R^2), the root mean square error (RMSE), and the percentage bias (PBIAS).

i. The coefficient of determination (R^2) quantifies the strength of the linear association between observed and simulated fluxes:

$$R^2 = \left\{ \frac{\sum_{i=1}^{n}(O_i-\bar{O})(P_i-\bar{P})}{[\sum_{i=1}^{n}(O_i-\bar{O})^2]^{0.5}\,[\sum_{i=1}^{n}(P_i-\bar{P})^2]^{0.5}} \right\}^2 \quad (4)$$

ii. RMSE provides a measure of the overall magnitude of simulation errors.

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2\right]^{0.5} \quad (5)$$

iii. PBIAS indicates the average tendency of the model to overestimate or underestimate the observed values.

$$PBIAS = 100\,\frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n} O_i} \quad (6)$$

To further perform diagnostic analysis, the slope of $GPP \cdot VPD^{0.5}$ -ET relationship called as underlying water use efficiency (uWUE) was examined using both observations and model simulations. ~~To further perform diagnostic analysis, the relationship between $GPP \cdot VPD^{0.5}$ and ET was examined using both observations and model simulations.~~ This analysis was restricted

to periods of peak leaf area index (LAI > 1.5 m^2 m^{-2}) to minimize soil evaporation contributions and isolate canopy-level stomatal behaviour. Additionally, the response of evaporative fraction (EF = $\frac{LE}{H+LE}$) to VPD was analysed using half-hourly averages during peak photosynthetic periods (11:00-15:00) within the active growing phase to assess the ability of the ISBA-A-g_s model to capture land-atmosphere coupling and surface energy partitioning under contrasting irrigation and hydro-climatic conditions.

3.0 Results

3.1~~2~~ Dynamics of GPP, ET, and WUE ~~gross primary productivity, evapotranspiration, and water use efficiency~~

Figure 5 presents seasonal boxplots of GPP, ET, and WUE, highlighting the substantial interannual variability across the FR-Lam and Ind-IITH sites. At FR-Lam, seasonal mean GPP ranged from -8 to -11 gC m^{-2} day^{-1}, with the strongest carbon uptake observed in 2015, whereas 2010 exhibited comparatively lower GPP, corresponding to the wet and dry growing seasons, respectively. Similarly, ET displayed considerable interannual variability, with 2015 showing the highest upper whisker and 2008 the lowest, suggesting large differences in seasonal evaporative demand and canopy water fluxes. In contrast, WUE exhibited an inverse pattern, with the highest values recorded in 2008, whereas 2010 and 2015 showed comparatively lower WUE. Despite relatively high GPP in 2012, WUE remained moderate because the increase in carbon uptake was accompanied by a concurrent increase in ET.

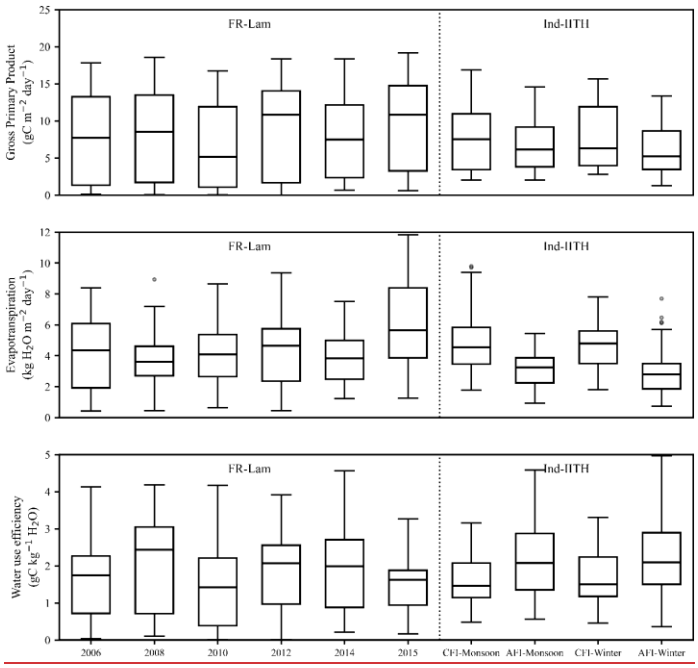
At Ind-IITH, GPP exhibited overlapping interquartile ranges between CFI and AFI during the monsoon season and showed similar magnitudes with only subtle variability during the winter. However, relative to CFI, AFI reduced seasonal GPP by __% during the monsoon and __% during the winter. These distribution patterns indicate that irrigation strategy had a limited influence on seasonal carbon assimilation compared with the inherent seasonal

variability. During the monsoon season, AFI reduced ecosystem ET by 32-35% relative to CFI. A similar, but more pronounced, reduction was observed during the winter season, when AFI decreased ET by 40-42% compared with CFI. Despite comparable GPP between irrigation treatments, AFI increased ecosystem WUE by 40% and __% relative to CFI during the monsoon and winter seasons, respectively. This improvement was primarily driven by reduced ET rather than changes in GPP. Overall, these findings indicate that irrigation management exerted a stronger influence on ecosystem ET than on GPP, thereby increasing ecosystem WUE at the Ind-IITH site.

A cross-site comparison further highlights that WUE variability is governed by different mechanisms at the FR-Lam and Ind-IITH sites, despite exhibiting broadly comparable magnitudes. At FR-Lam, WUE was primarily controlled by interannual climatic variability, with higher values observed during drier years (e.g. 2008) and lower WUE observed in wet year (e.g. 2015). In contrast, at Ind-IITH, WUE was more strongly influenced by irrigation management than by seasonal carbon assimilation, with AFI consistently enhancing WUE relative to CFI. Despite these contrasting controls, the overall range of WUE remained broadly similar between the temperate and semi-arid environments, indicating that both climatic variability and irrigation management can produce comparable ecosystem-scale WUE's through different underlying mechanisms.

~~Seasonal boxplots revealed substantial interannual variability in gross primary productivity (GPP), evapotranspiration (ET), and water use efficiency (WUE) estimated across the six maize growing seasons at the FR-Lam site and the two seasons at the Ind-IITH site with the 2 irrigation treatments (Figure 5). At FR-Lam, the seasonal mean GPP ranged from -8 to -11 gC m^{-2} day^{-1}, with the strongest carbon uptake observed in 2012 and 2015 (~10 to -11 gC m^{-2} day^{-1}). In contrast, 2010 exhibited comparatively lower GPP (~6 gC m^{-2} day^{-1}). These results demonstrate marked interannual differences in seasonal carbon assimilation. Seasonal ET~~

~~varied between 3.5 to 5.8 kg H_2O m^{-2} day^{-1}. The maximum ET occurred in 2015, accompanied by the largest upper range values (12 kg H_2O m^{-2} day^{-1}) and the minimum ET observed in 2008 (3.5 kg H_2O m^{-2} day^{-1}). Across seasons, ET distributions showed substantial dispersion, reflecting strong variability in daily evaporative demand and canopy water flux. WUE ranged from 1.6 to 2.6 gC kg^{-1} H_2O over the seasons. Peak WUE was recorded in 2008 (2.4–2.6 gC kg^{-1} H_2O), while 2010 and 2015 exhibited comparatively lower values (1.5–1.8 gC kg^{-1} H_2O). Despite high carbon uptake in 2012, WUE remained moderate due to concurrent increases in ET. At Ind-IITH, GPP ranged from 6 to 8 gC m^{-2} day^{-1}, with overlapping interquartile ranges between CFI and AFI during the monsoon. In Winter, GPP were of similar magnitude (5–7 gC m^{-2} day^{-1}), and variability remained substantial between the treatments. The distribution patterns indicate that the irrigation strategy had a limited influence on seasonal carbon assimilation compared to the intrinsic seasonal variability. In contrast, ET showed clear and consistent differences between irrigation treatments. During monsoon, CFI exhibited higher ET (4.5–5.0 kg H_2O m^{-2} day^{-1}) compared to AFI (3.0–3.5 kg H_2O m^{-2} day^{-1}). A similar reduction under AFI was observed during winter, and ET under CFI (4.5–5.0 kg H_2O m^{-2} day^{-1}) exceeded that under AFI (2.5–3.0 kg H_2O m^{-2} day^{-1}). These patterns indicate that AFI consistently reduced seasonal water loss relative to CFI. Despite similar magnitudes of GPP between treatments, AFI resulted in higher WUE in both seasons. During Monsoon, WUE under AFI ranged from 2.0 to 2.2 gC kg^{-1} H_2O, compared to 1.4 to 1.6 gC kg^{-1} H_2O under CFI. A comparable enhancement was observed in winter, with AFI maintaining higher WUE relative to CFI. The improvement in WUE under AFI primarily corresponded to reductions in ET rather than substantial differences in GPP. Overall, irrigation treatment in the Ind-IITH site exerted a stronger influence on ET and WUE than on GPP.~~


FR-Lam
Ind-IITH
Gross Primary Product (gC m^{-2} day^{-1})
Evapotranspiration (kg H$_2$O m^{-2} day^{-1})
Water use efficiency (gC kg^{-1} H$_2$O)
2006
2008
2010
2012
2014
2015
CFI-Monsoon
AFI-Monsoon
CFI-Winter
AFI-Winter

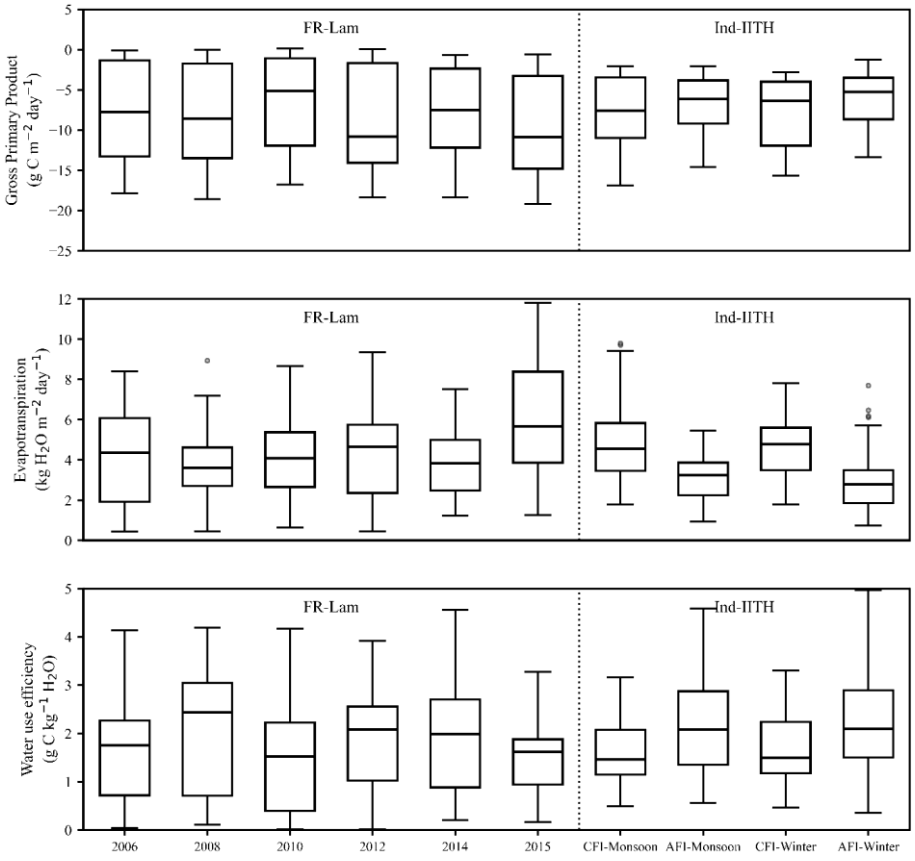


Figure 5. Seasonal variability of gross primary productivity (GPP), evapotranspiration (ET), and water use efficiency (WUE) during six maize growing seasons (2006, 2008, 2010, 2012, 2014, and 2015) at the FR-Lam site and four treatments considered at the Ind-IITH site.

~~A cross-site comparison further highlights that WUE variability emerges from different controlling mechanisms at FR-Lam and Ind-IITH, despite exhibiting comparable magnitudes overall. At FR-Lam, WUE was primarily governed by interannual climatic variability, with higher values observed during relatively warmer and drier years (e.g., 2008), where reduced ET relative to carbon uptake enhanced efficiency. In contrast, at Ind-IITH, WUE was more strongly influenced by irrigation management than by seasonal carbon assimilation, with AFI~~

~~consistently improving WUE compared to CFI through systematic reductions in ET while maintaining similar GPP levels. Despite these differing controls, the range of WUE values remained broadly similar between the temperate (FR-Lam) and semi-arid (Ind-IITH) environments, indicating that both climatic variability and irrigation strategies can lead to comparable ecosystem-scale efficiencies via different pathways. Notably, higher WUE under warmer conditions at FR-Lam and under water-saving irrigation (AFI) at Ind-IITH suggests that reductions in non-productive water losses play a key role in enhancing WUE across contrasting climates. Overall, these findings demonstrate that while WUE magnitude may be similar across sites, its underlying drivers differ fundamentally, being climate-driven at FR-Lam and management-driven at Ind-IITH.~~

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3.2~~3~~ Model calibration

Table 3 summarizes the calibrated optimal parameter estimates of the ISBA-A-g_s model for the FR-Lam. Among the 12 parameters investigated, five parameters (gm, GC, F2I, RE25, and D_{Max}) were identified as particularly sensitive. Results shows that the reduction in mesophyll conductance (gm) from its initial value indicates greater internal CO_2 diffusion limitations, reflecting stronger mesophyll constraints on carbon assimilation under contrasting environmental conditions. The optimized upper-bound value of cuticular conductance (GC) indicates a substantial contribution of cuticular water loss to total transpiration, particularly during dry periods. The optimized F2I parameter suggests that soil moisture stress begins to constrain carbon-water flux coupling, reflecting moderate drought sensitivity of the ecosystem. The converged values of RE25 and D_{Max} indicate stable temperature-normalized respiratory fluxes and enhanced stomatal sensitivity to atmospheric VPD, supporting the observed regulation of transpiration under dry atmospheric conditions. Overall, the calibrated parameters

indicate that the FR-Lam site is characterized by relatively high cuticular conductance and strong atmospheric control of stomatal behaviour.

~~Table 5 summarizes the calibrated parameter ranges, initial values, and optimal estimates of the ISBA-A-g_s model for the FR-Lam. Among the 12 parameters investigated, five parameters (gm, GC, F2I, RE25, and D_{Max}) were identified as particularly sensitive. Mesophyll conductance (gm) was explored within a range of 1×10^{-3} to 3×10^{-2} m s^{-1}, with an initial value of 7.53×10^{-2} m s^{-1} and converged to 2×10^{-3} m s^{-1}, which may indicate relatively moderate internal CO_2 diffusion constraints. The reduction from the initial value suggests tighter mesophyll limitation under site-specific environmental conditions. Cuticular conductance (GC) was varied between 1.5 to 4.5×10^{-4} m s^{-1}, with an optimal estimate of 4.2×10^{-4} m s^{-1}. The optimized value being close to the upper bound could imply a strong contribution of cuticular water loss to total transpiration, particularly under elevated atmospheric demand during dry seasons. The critical normalized soil water content for stress parameterization (F2I) converges to an optimal value of 0.334. This may suggest that soil moisture stress begins to significantly regulate carbon-water flux coupling at one-third of normalized soil water availability is depleted, reflecting moderate drought sensitivity. The ecosystem respiration parameter at 25°C (RE25) was tested between 2 to 3×10^{-7} kg/kg m s^{-1}, with an optimal value of 2.50×10^{-7} kg/kg m s^{-1} indicating stable temperature-normalized respiratory flux representation. The maximum leaf to air saturation deficit (D_{Max}) was constrained between 0.05 and 0.5 kg kg^{-1}, with calibration yielding an optimal value of 0.065 kg kg^{-1}, which may indicate strong stomatal sensitivity to atmospheric VPD, consistent with observed transpiration regulation under dry air conditions. Overall, the calibrated parameters reflect FR-Lam site is characterized by moderate mesophyll diffusion capacity, appreciable cuticular conductance, intermediate soil moisture stress sensitivity, stable respiratory scaling, and strong atmospheric control on stomatal behaviour. These optimized values improved the representation of GPP,~~

~~ET, and WUE at the FR-Lam site, reducing bias and improving model-observation agreement (Supplementary Table S1-S2).~~

Table ~~5~~3. Calibrated ISBA-A-g_s model parameters for the FR-Lam experimental site.

Description	Symbol	Value Range	Initial value considered	Optimal Value	Reference
Mesophyll conductance	gm	1×10^{-3} - 3×10^{-2}	7.53×10^{-3}	2×10^{-3}	(Calvet, 2000)
Cuticular conductance	GC	1.5 - 4.5 $\times 10^{-4}$	4×10^{-4}	4.2×10^{-4}	(Gibelin et al., 2006)
Critical normalized soil water content for stress parameterization	F2I	0.2 - 0.5	0.20	0.334	(Calvet, 2000)
Ecosystem respiration parameter	RE25	2 to 3 $\times 10^{-7}$	2.88×10^{-7}	2.50×10^{-7}	(Gibelin et al., 2006)
Maximum leaf to air saturation deficit	D_{Max}	0.05 – 0.5	0.05	0.065	(Calvet, 2000)

Table 4 summarizes the calibrated optimal parameter estimates of the ISBA-A-g_s model at the Ind-IITH site. Among the 12 parameters investigated, five (gm, GC, F2I, RE25, and D_{Max}) were identified as particularly sensitive. Results show that the lower value of optimal mesophyll conductance (gm) under AFI during the monsoon reflected stronger internal CO_2 diffusion limitations, leading to a minimal reduction in GPP while reducing ET to a greater extent, thereby enhancing WUE. In contrast, slightly higher gm during AFI in winter favoured carbon assimilation under given atmospheric demand. The calibrated GC values remained low across all treatments, with marginally higher values under CFI during winter, indicating greater cuticular water loss under fully irrigated conditions. The calibrated F2I values in AFI were

observed to be higher during winter, indicating stronger soil moisture control on stomatal regulation under dry conditions and promoting earlier reductions in transpiration. The parameters such as RE25 and D_{Max} showed marginal variations across treatments, indicating seasonal changes in respiration and moderate atmospheric control that reduced ET under high VPD while maintaining stable WUE. Overall, the calibrated parameters under AFI indicated subtle reductions in mesophyll conductance and soil moisture stress thresholds, reflecting physiological optimization under alternate wetting and drying conditions in the semi-arid agroecosystem. These optimized parameter values improved the representation of GPP, ET, and WUE, reducing model bias and enhancing agreement between simulated and observed fluxes (Table S3-S4). Together, these results demonstrate the capability of the ISBA-A-g_s model to mechanistically represent irrigation-driven ecosystem carbon-water interactions under contrasting temperate and tropical semi-arid hydro-climatic conditions within the scope of the available observations, which constitutes the principal scientific contribution of this study.

~~Table 6 summarizes the calibrated parameter ranges, initial values, and optimal estimates of the ISBA-A-g_s model for maize under CFI and AFI treatments during the monsoon and winter seasons at the Ind-IITH. Among the 12 parameters investigated, five (gm, GC, F2I, RE25, and D_{Max}) were identified as particularly sensitive. Mesophyll conductance (gm) exhibited lower optimized values under AFI compared to CFI during the monsoon (2.2×10^{-3} vs 2.5×10^{-3} m s^{-1}), indicating a mild limitation in internal CO_2 diffusion under partial root-zone drying. This reduction moderated GPP but limited excessive transpiration, thereby contributing to improved WUE under AFI (Al-Kayssi, 2023; Reavis et al., 2024). In contrast, marginally higher winter gm supported enhanced carbon gain under lower atmospheric demand. The GC remained within the lower range ($2.9–3.5 \times 10^{-4}$ m s^{-1}) across treatments, with marginally higher values under CFI during winter, reflecting slightly enhanced non-stomatal~~

~~water loss under fully irrigated conditions. The F2I ranged between 0.400 and 0.412, with consistently higher values during winter, suggesting stronger soil moisture control on stomatal regulation in the dry season. The critical soil moisture threshold (F2I ≈ 0.40–0.41) exerted strong control on ET variability, particularly under AFI, indicating that the earlier stomatal regulation under declining soil moisture reduced transpiration without proportionally suppressing GPP. The 'RE25' varied from 2.20 to 2.40 × 10^{-7} kg/kg m s^{-1}, with slightly elevated values during winter, consistent with seasonal temperature regulation of respiration processes. The optimized D_{Max} values (0.070–0.075) indicated moderate atmospheric control, constraining ET under high VPD while stabilizing WUE. Overall, AFI treatments showed subtle reductions in gm and RE25, along with slight adjustments in soil moisture stress thresholds, reflecting physiological optimization under alternate wetting and drying conditions in the Indian semi-arid agroecosystem.~~

Table ~~6~~4. Calibrated ISBA-A-g_s model parameters for the Ind-IITH experimental site.

Description	Symbol	Value Range	Initial value considered	Optimal Value				References
				CFI - Monsoon	AFI - Monsoon	CFI - Winter	AFI - Winter	
Mesophyll conductance	gm	1 × 10^{-3} - 3 × 10^{-2}	7.53 × 10^{-3}	2.5 × 10^{-3}	2.2 × 10^{-3}	2.8 × 10^{-3}	2.7 × 10^{-3}	(Calvet, 2000)
Cuticular conductance	GC	1.5 - 3.0 × 10^{-4}	4 × 10^{-4}	3 × 10^{-4}	2.9 × 10^{-4}	3.5 × 10^{-4}	3.2 × 10^{-4}	(Gibelin et al., 2006)

Critical normalized soil water content for stress parameterization	F2I	0.21 - 0.48	0.20	0.40 0	0.405	0.412	0.409	(Calvet, 2000)
Ecosystem respiration parameter	RE25	2 to 3 × 10^{-7}	2.88 × 10^{-7}	2.20 × 10^{-7}	2.22 × 10^{-7}	2.32 × 10^{-7}	2.40 × 10^{-7}	(Gibelin et al., 2006)
Maximum leaf to air saturation deficit	D_{Max}	0.05 - 0.45	0.04	0.07 0	0.071	0.075	0.071	(Calvet, 2000)

3.34 Model performance ~~over the FR-Lam site~~

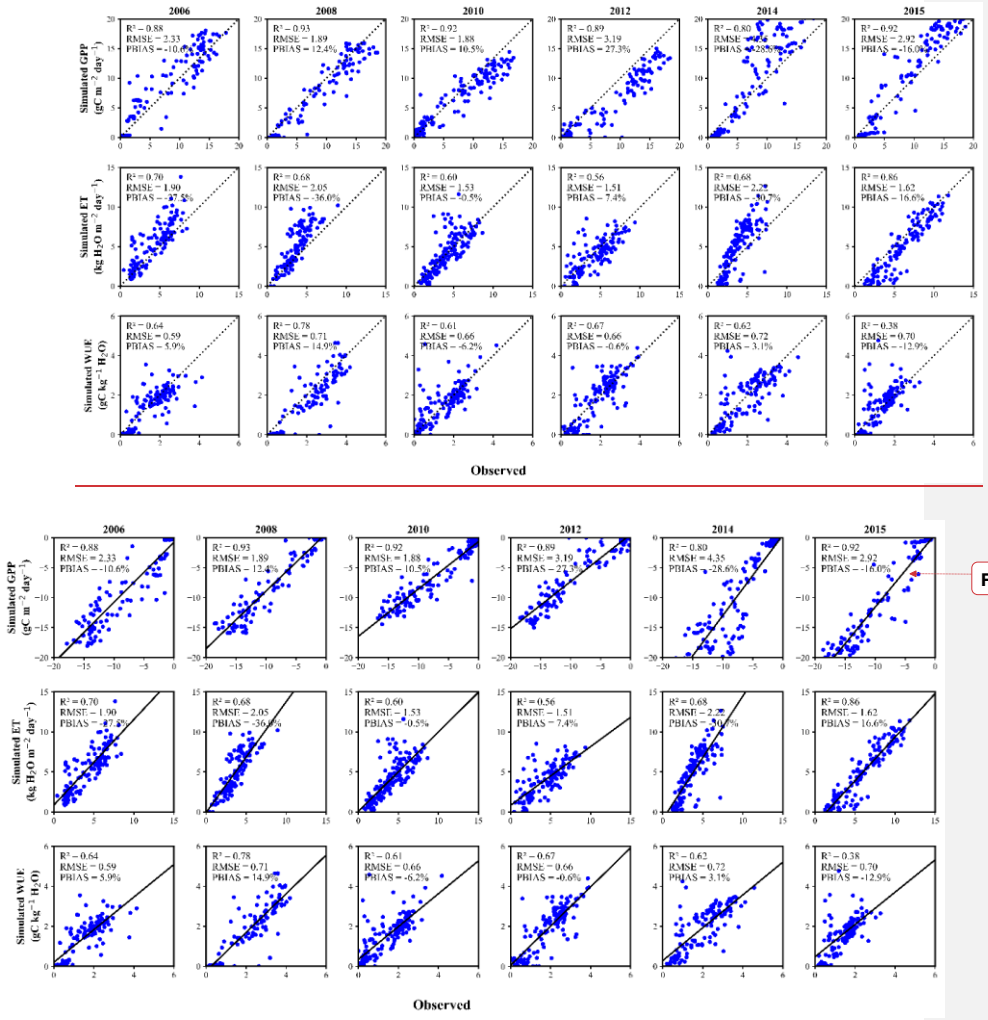
3.3.1 FR-Lam site

The calibrated ISBA-A-g_s model demonstrated strong potential in reproducing GPP, ET, and WUE dynamics at the FR-Lam site (Figure 6). GPP was simulated with high accuracy (R^2 ranging from 0.80 to 0.93), successfully capturing both dry (2008) and wet (2014) conditions, indicating robust representation of photosynthetic processes across moisture ~~gradients~~conditions. Low RMSE and moderate PBIAS further confirmed reliable GPP estimates, although systematic overestimation was evident in 2014 (-28%) and 2015 (-16%), suggesting enhanced simulated carbon assimilation under non-water-limited conditions. ET simulations also showed moderate to strong agreement with observations (R^2 = 0.60-0.86), with the best performance during the wet year of 2015, reflecting improved representation of

atmospheric demand and surface conductance. In contrast, larger RMSE and PBIAS during the dry year of 2008 (RMSE = 2.05 kg H_2O m^{-2} day^{-1}; PBIAS = -36.0%) indicate greater sensitivity to seasonal variations in soil moisture availability and evaporative demand. WUE exhibited comparatively better performance (R^2 = 0.38-0.78); however, because it is derived from both GPP and ET, minor deviations in ET during 2015 propagated through the GPP/ET ratio, resulting in larger fluctuations in WUE (RMSE = 0.70 gC kg^{-1} H_2O; PBIAS = -12.9%). Overall, the calibrated ISBA-A-g_s model effectively captured ecosystem-scale carbon and water dynamics, with the strongest performance for GPP, robust simulation of ET, and comparatively greater uncertainty in WUE arising from propagated errors in GPP and ET.

~~The low RMSE and moderate PBIAS further confirm reliable simulation of seasonal carbon uptake, although systematic overestimation was evident in 2014 (~28%) and 2015 (~16%), suggesting enhanced modelled assimilation under non-water-limited conditions. ET simulations exhibited moderate to strong agreement with observations (R^2 of 0.60 in 2012 to 0.86 in 2015), reflecting the model's ability to reproduce canopy-atmosphere water exchange (Dare-Idowu et al., 2021). Strong performance in 2015 indicates improved representation of atmospheric demand and surface conductance dynamics during wet conditions, whereas larger dispersion and PBIAS in 2008 (RMSE: 2.05 Kg H_2O m^{-2} day^{-1}; PBIAS: -36.0%) suggest sensitivity to seasonal variations in soil moisture availability and evaporative demand. In contrast, WUE showed comparatively better performance (R^2 of 0.38 to 0.78), consistent with the propagation of uncertainties from both GPP and ET simulations. As WUE sensitive with the changes in ET, and this sensitivity is clearly evident in 2015, where minor deviations in ET resulted in disproportionately larger fluctuations (RMSE: 0.70 gC Kg^{-1} H_2O; PBIAS: -12.9%) in WUE. Despite this, the model adequately captured the overall magnitude and interannual variability of WUE, with RMSE lower than 0.75 gC kg^{-1} H_2O. Overall, the calibrated ISBA-A-g_s framework effectively represents coupled carbon-water processes at the ecosystem scale,~~

~~demonstrating strongest performance for GPP and comparatively moderate uncertainty for WUE.~~



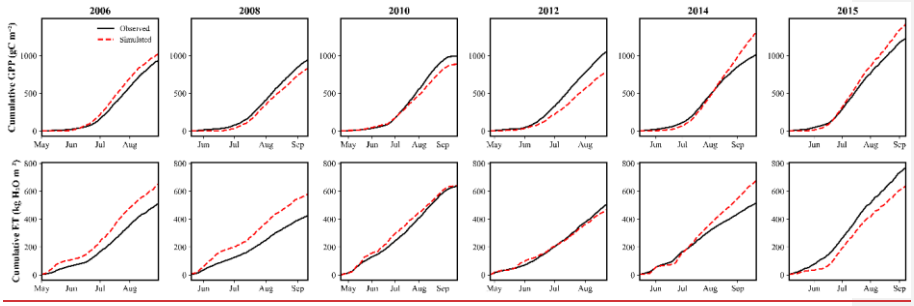
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Figure 6. Scatter plots comparing daily eddy covariance observations with ISBA-A-g_s simulated gross primary productivity (GPP: first row), evapotranspiration (ET: second row), and water use efficiency (WUE: third row) at the FR-Lam site during six maize growing seasons (2006, 2008, 2010, 2012, 2014, and 2015). Statistical performance metrics, including the coefficient of determination (R^2), root mean square error (RMSE), and percentage bias (PBIAS), are reported in each panel.

The cumulative observed and simulated flux dynamics revealed pronounced interannual variability in seasonal GPP and ET at the FR-Lam site (Figure 7). Cumulative GPP ranged from 900 gC m^{-2} in 2008 to a peak of 1500 gC m^{-2} in 2015, corresponding to relatively dry and wet growing seasons, respectively. The steep increase in cumulative GPP during the peak growing period (May-August) reflected enhanced canopy photosynthesis associated with maximum leaf area development. Accordingly, mean seasonal GPP accumulation rates (temporal slope of the cumulative curves) were highest in 2015 (observed: 11.61; simulated: 12.10 gC m^{-2} day^{-1}) and lowest in 2008 (observed: 9.11; simulated: 8.07 gC m^{-2} day^{-1}). Similarly, cumulative ET ranged from 500 kg H_2O m^{-2} in 2008 to a peak of 800 kg H_2O m^{-2} in 2015, reflecting the relatively dry and wet growing seasons, respectively. Mean seasonal ET accumulation rates were also highest in 2015 (observed: 6.73; simulated: 5.76 kg H_2O m^{-2}) and lowest in 2008 (observed: 3.80; simulated: 4.19 kg H_2O m^{-2}). Overall, the simulated cumulative GPP and ET closely reproduced the observed seasonal patterns, although slight overestimation of GPP was evident in 2014 and 2015 and deviations in cumulative ET occurred in 2008 and 2014, likely reflecting model sensitivity to atmospheric dryness. Nevertheless, the close agreement between simulated and observed cumulative fluxes demonstrates that the calibrated ISBA-A-g_s model effectively captured seasonal carbon and water dynamics at the FR-Lam site.

~~The cumulative observed and simulated flux dynamics reveal pronounced interannual variability in seasonal GPP and ET at the FR-Lam site (Figure 7). Cumulative GPP ranged from -900 to -1500 gC m^{-2}, with the highest uptake observed in 2014 and 2015, and comparatively lower values in 2006 and 2008. The rapid slope in cumulative GPP during the peak growth phase (May-August) reflects intensified canopy photosynthesis, corresponding to maximum leaf area development. Quantitatively, the mean seasonal GPP accumulation rates (slope of cumulative curves) varied from -7.92 to -11.16 gC m^{-2} day^{-1} for observations and -6.87 to -12.91 gC m^{-2} day^{-1} for simulations, with higher values during 2015 (observed: -11.61;~~

~~simulated: -12.10 gC m^{-2} day^{-1}) and lower values during 2008 (observed: -9.11; simulated: -8.07 gC m^{-2} day^{-1}). Simulated cumulative GPP closely tracked observations in most years, although noticeable overestimation occurred in 2014 and 2015. Cumulative ET varied between 500 and 800 kg H_2O m^{-2} across seasons, with wet years (e.g. 2014 and 2015) exhibiting greater total water loss than dry years (e.g. 2006 and 2008). The steepest accumulation rates were observed during mid-season (May-September). The seasonal ET accumulation rates ranged from 3.860 to 6.730 kg H_2O m^{-2} day^{-1} (observed) and 4.075 to 5.768 kg H_2O m^{-2} day^{-1} (simulated), with higher values during 2015 (observed: 6.73; Simulated: 5.76 kg H_2O m^{-2} day^{-1}) and lower values in 2008 (observed: 3.80; Simulated: 4.19 kg H_2O m^{-2} day^{-1}). While the model reproduced the seasonal trajectory of ET, deviations in total seasonal ET were evident in 2008 and 2014, suggesting model dependency on atmospheric dryness. Seasonal observed WUE ranged from 1.60 to 2.22 g C kg^{-1} H_2O, while simulated values ranged from 1.37 to 2.21 g C kg^{-1} H_2O, reflecting the integrated balance between carbon gain and water loss. Years characterized by lower evapotranspiration (e.g., 2008) exhibited higher WUE (observed: 2.22 g C kg^{-1} H_2O; simulated: 1.50 g C kg^{-1} H_2O), whereas seasons with relatively higher ET (e.g., 2015) resulted in reduced WUE (observed: 1.60 g C kg^{-1} H_2O; simulated: 1.80 g C kg^{-1} H_2O). Overall, the close agreement between simulated and observed values across seasons indicates that the calibrated ISBA-A-g_s model effectively captures both daily variability and seasonal-scale carbon-water dynamics, with only minor discrepancies.~~



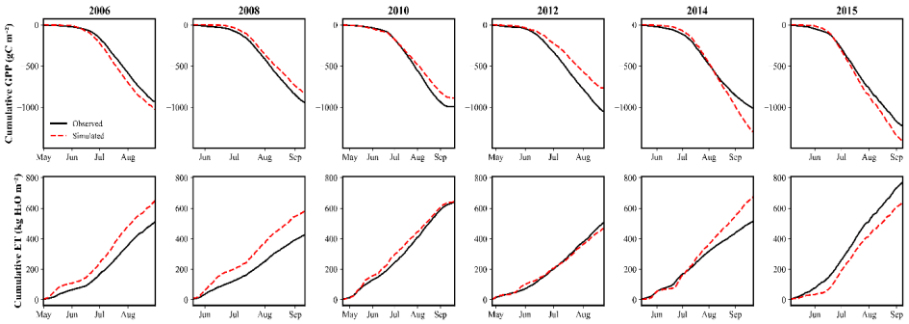


Figure 7. Cumulative plots by accumulating daily eddy covariance observations with ISBA-A-g_s simulated gross primary productivity (GPP: first row) and evapotranspiration (ET: second row) at the FR-Lam site during six maize growing seasons (2006, 2008, 2010, 2012, 2014, and 2015).

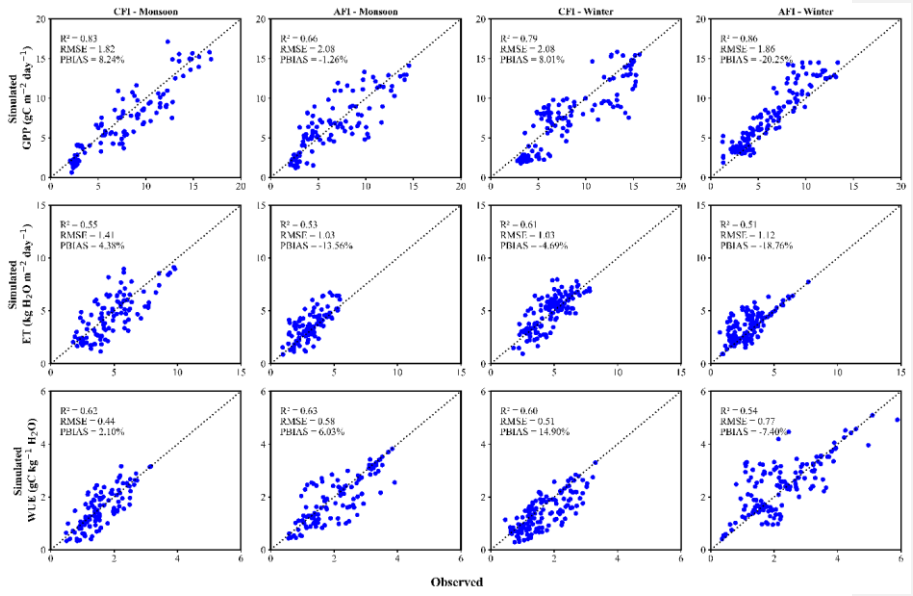
3.3.2~~3.5 Model performance over the~~ Ind-IITH site

The calibrated ISBA-A-g_s model showed robust performance in simulating GPP, ET, and WUE across irrigation treatments and seasons at the Ind-IITH site (Figure 8).). During the monsoon, GPP was accurately reproduced under both irrigation treatments, with better performance under CFI (R^2 = 0.83) than AFI (R^2 = 0.66), while maintaining low model bias. During winter, GPP simulation improved further, particularly under AFI (R^2 = 0.86), although it was systematically overestimated. These results indicate that the model effectively captured seasonal photosynthetic dynamics, with slightly higher uncertainty under AFI during the monsoon due to the dominant influence of precipitation over irrigation. ET simulations showed moderate agreement across all treatments (R^2 = 0.51-0.61), with comparable performance during the monsoon and winter. However, ET was consistently overestimated under AFI, particularly during winter (PBIAS = -18.76%), indicating greater uncertainty under water-limited conditions. During the monsoon, WUE was well reproduced under both irrigation treatments, with similar performance (R^2 = 0.62-0.63) and low overall model bias, although AFI showed slight underestimation than CFI. During winter, WUE performance remained

consistent (R^2 = 0.60 for CFI and 0.54 for AFI), with PBIAS ranging from -7.40% to 14.90%. Overall, the calibrated ISBA-A-g_s model showed the strongest performance for GPP, followed by ET and WUE, reflecting the propagation of uncertainties from both GPP and ET simulations, while AFI introduced slightly greater variability in ET and WUE than CFI.

~~For GPP, model performance was consistently strong, with R^2 ranging from 0.66 under AFI-Monsoon to 0.86 under AFI-Winter. In the CFI-Monsoon, GPP was reproduced with high accuracy (R^2 = 0.83; RMSE = 1.82 gC m^{-2} day^{-1}; PBIAS = 8.24%), indicating a slight underestimation of carbon uptake. Under AFI-Monsoon, performance decreased moderately (R^2 = 0.66; RMSE = 2.08 gC m^{-2} day^{-1}), although bias was minimal (PBIAS = -1.26%). During winter, model performance improved further, particularly under AFI (R^2 = 0.86; RMSE = 1.86 gC m^{-2} day^{-1}), although a systematic overestimation of GPP was observed (PBIAS = -20.25%). These results suggest that the model effectively captures seasonal photosynthetic dynamics, with slightly higher uncertainty under AFI during monsoon conditions due to the dominant influence of precipitation over irrigation inputs. ET simulations showed moderate agreement across treatments, with R^2 ranges between 0.51 and 0.61 during winter and between 0.53 and 0.55 during monsoon. In CFI-Monsoon, ET was simulated moderately (R^2 = 0.55; RMSE = 1.41 kg H_2O m^{-2} day^{-1}; PBIAS = 4.38%), indicating minor underestimation. Under AFI-Monsoon, bias shifted negative (PBIAS = -13.56%), suggesting overestimation of ET. Winter performance remained comparable (R^2 of 0.61 for CFI and 0.51 for AFI), although AFI-Winter exhibited larger overestimation (PBIAS = -18.76%). The relatively low R^2 values for ET compared to GPP reflect the stronger sensitivity of water fluxes to short-term meteorological variability and soil moisture dynamics, and higher heterogeneity for AFI treatment. WUE exhibited comparatively moderate performance, with R^2 ranging from 0.54 to 0.63. Under CFI-Monsoon, WUE was simulated strongly, indicating better agreement and minimal bias (R^2 = 0.62; RMSE = 0.44 gC kg^{-1} H_2O; PBIAS = 2.10%). AFI-Monsoon showed similar performance~~

~~(R^2 = 0.63; RMSE = 0.58 gC kg^{-1} H_2O), although with moderate underestimation (PBIAS = 6.03%). During winter, WUE performance remained consistent (R^2 = 0.60 for CFI and 0.54 for AFI), with bias ranging from -7.40% to 14.90%. The comparatively lower R^2 for WUE reflects the propagation of uncertainties from both GPP and ET simulations, as small deviations in ET can induce amplified variability in WUE simulations. Overall, model performance was strongest for GPP, moderate for ET, and WUE simulations. Seasonal contrasts indicate that the ISBA-A-g_s model captures GPP more robustly than ET and WUE fluxes, while AFI introduces slightly higher variability in both ET and WUE simulations.~~



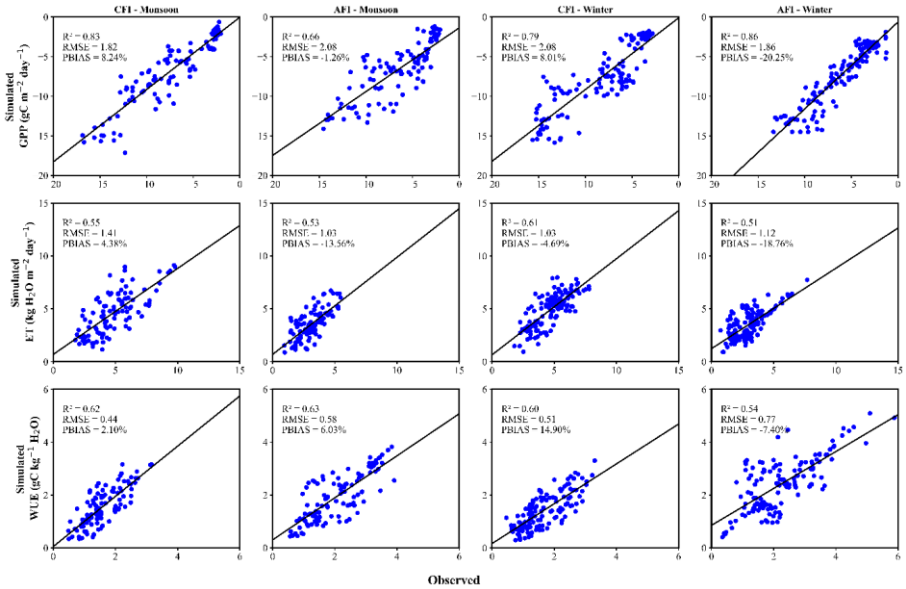


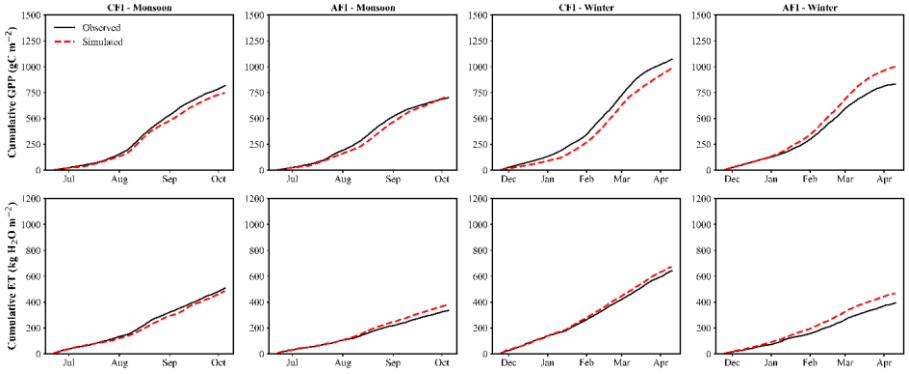
Figure 8. Scatter plots comparing daily eddy covariance observations with ISBA-A-g_s simulated gross primary productivity (GPP: first row), evapotranspiration (ET: second row), and water use efficiency (WUE: third row) at the Ind-IITH site during four maize treatments considered. Statistical performance metrics, including the coefficient of determination (R^2), root mean square error (RMSE), and percentage bias (PBIAS), are reported in each panel.

The cumulative seasonal patterns reveal clear contrasts in GPP and ET between irrigation treatments and crop seasons at the Ind-IITH site (Figure 9). Mean seasonal GPP accumulation rates (temporal slope of the cumulative curves) were consistently higher under CFI than AFI during both the monsoon (observed: 8.90 vs. 7.82; simulated: 8.21 vs. 7.68 gC m^{-2} day^{-1}) and winter (observed: 8.89 vs. 6.94; simulated: 8.04 vs. 8.32 gC m^{-2} day^{-1}), although the model slightly overestimated carbon uptake under AFI during the winter growing season, particularly during the late reproductive stage. Additionally, the steeper mid-season slope (January-March) reflects enhanced radiation availability and sustained canopy activity during winter. Mean seasonal ET accumulation rates were consistently higher under CFI than AFI during both the monsoon (observed: 4.97 vs. 3.25; simulated: 4.66 vs. 3.74 kg H_2O m^{-2} day^{-1}) and winter (observed: 4.80 vs. 3.02; simulated: 5.10 vs. 3.68 kg H_2O m^{-2} day^{-1}), with a more pronounced divergence between irrigation treatments during winter, indicating greater sensitivity of ET to irrigation management under drier atmospheric conditions. Overall, the close agreement between observed and simulated cumulative GPP and ET demonstrates the

capability of the ISBA-A-g_s model to represent seasonal carbon assimilation and evapotranspiration dynamics across the contrasting irrigation treatments and crop seasons.

~~During the monsoon, cumulative GPP reached to ~820 gC m^{-2} under CFI and ~780 gC m^{-2} under AFI. The corresponding seasonal GPP accumulation rates (slope of cumulative curves) were ~8.90 and ~7.82 gC m^{-2} day^{-1} for observed CFI and AFI, respectively, with simulated values of ~8.21 and ~7.68 gC m^{-2} day^{-1}. The close agreement between observed and simulated trajectories indicates that the model adequately captured seasonal carbon assimilation under monsoon conditions, although simulated GPP slightly overestimated during late-season phases in both treatments. In contrast, winter season GPP accumulation was substantially higher, reaching nearly ~1050 gC m^{-2} under CFI and approximately ~900 gC m^{-2} under AFI. The steeper mid-season slope (Jan–Mar) reflects enhanced radiation availability and sustained canopy activity during winter. Quantitatively, GPP accumulation rates were ~8.89 and ~6.94 gC m^{-2} day^{-1} for observed CFI and AFI, respectively, compared to ~8.04 and ~8.32 gC m^{-2} day^{-1} for simulations, indicating a tendency of the model to overestimate carbon uptake under AFI Winter, particularly during the late reproductive stage. These results indicate that winter conditions favoured greater seasonal carbon assimilation compared to monsoon, likely due to reduced cloud cover and more stable atmospheric demand. During the monsoon, total ET reached to 500 kg H_2O m^{-2} for CFI and around 380 kg H_2O m^{-2} for AFI. The reduced ET under AFI reflects lower water inputs and moderated transpiration rates. The seasonal ET accumulation rates were 4.97 and 3.25 kg H_2O m^{-2} day^{-1} for observed CFI and AFI, respectively, against simulated values of 4.66 and 3.74 kg H_2O m^{-2} day^{-1}. Simulated ET closely tracked observed patterns in CFI Monsoon, whereas slight overestimation was evident in AFI Monsoon during mid-season. Winter ET was substantially higher, reaching to 650 kg H_2O m^{-2} under CFI and 450 kg H_2O m^{-2} under AFI. The corresponding ET accumulation rates were 4.80 and 3.02 kg H_2O m^{-2} day^{-1} for observed CFI and AFI, compared to 5.10 and 3.68 kg H_2O m^{-2} day^{-1} for simulations. The~~

~~larger seasonal ET under winter suggests stronger evaporative demand. Notably, the divergence between CFI and AFI was more pronounced during winter, indicating enhanced sensitivity of transpiration to irrigation management under drier atmospheric conditions. These relatively temperate-like conditions, characterized by lower humidity and higher evaporative demand, tend to amplify the differences between irrigation methods, where CFI promotes higher soil moisture availability and transpiration, while AFI regulates water supply and limits excessive evaporative losses. During the monsoon season, observed WUE was 1.55 g C kg^{-1} H_2O under CFI and 1.61 g C kg^{-1} H_2O under AFI, while the corresponding simulated values were 1.54 and 1.86 g C kg^{-1} H_2O, respectively. The higher WUE under AFI indicates enhanced carbon gain per unit water consumed, likely driven by partial stomatal regulation and more conservative water use under alternate irrigation practices. In winter, observed WUE increased further, reaching 1.67 g C kg^{-1} H_2O under CFI and approximately 1.82 g C kg^{-1} H_2O under AFI, whereas simulated values were 1.46 and 2.13 g C kg^{-1} H_2O, respectively. Overall, the model successfully captured the seasonal WUE, although minor deviations were observed during the late-season period, particularly under AFI conditions in winter.~~



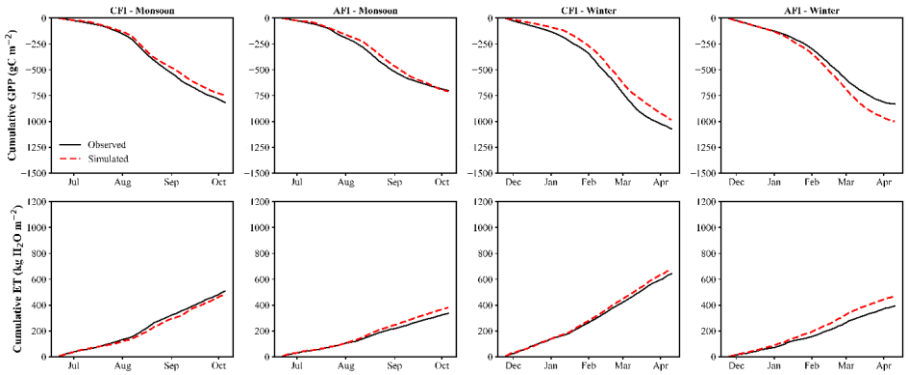


Figure 9. Cumulative plots by accumulating daily eddy covariance observations with ISBA-A-g_s simulated gross primary productivity (GPP: first row) and evapotranspiration (ET: second row) at the Ind-IITH site for four maize treatments considered.

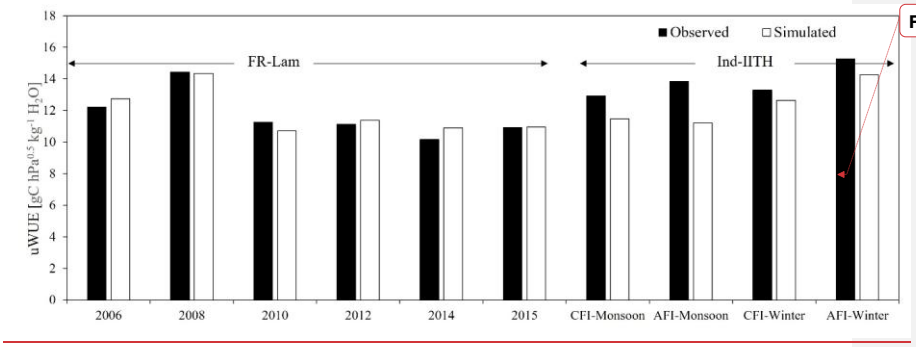
~~3.6 Model assessment~~ 3.4 Diagnostic analysis

Figure 10 illustrates variations in underlying water use efficiency (uWUE: slope of the GPP·VPD$^{0.5}$-ET relationship) at the FR-Lam and Ind-IITH sites, where steeper slopes indicate greater carbon gain per unit water loss through stronger stomatal regulation. At FR-Lam, observed uWUE ranged from 14.44 gC hPa$^{0.5}$ kg^{-1} H_2O in 2008 to 10.15 gC hPa$^{0.5}$ kg^{-1} H_2O in 2014, corresponding to relatively dry and wet years, respectively. The ISBA-A-g_s model closely reproduced this interannual variability, with simulated slopes differing by less than ±0.36 gC hPa$^{0.5}$ kg^{-1} H_2O from observations. At Ind-IITH, uWUE slopes were consistently steeper than those at FR-Lam, particularly during winter. During both seasons, observed uWUE was higher under AFI than CFI, suggesting stronger atmospheric control under alternate furrow irrigation. The ISBA-A-g_s model accurately reproduced these seasonal and treatment differences, with simulated slopes differing by less than ±0.74 gC hPa$^{0.5}$ kg^{-1} H_2O from observations, although slope magnitude was slightly underestimated under AFI. Overall, the

steeper slopes at Ind-IITH relative to FR-Lam indicate stronger carbon-water coupling and greater ecosystem sensitivity to atmospheric demand under semi-arid tropical conditions.

~~Figure 10 illustrates the variability in the slope of the GPP.VPD$^{0.5}$ – ET relationship at both FR-Lam and Ind-IITH sites. This slope represents an ecosystem-scale coupling between carbon assimilation and evapotranspiration. A higher slope indicates more efficient carbon gain per unit water loss, associated with stronger stomatal regulation, whereas a lower slope suggests increased water loss relative to carbon uptake and reduced efficiency. At FR-Lam, observed slopes ranged from -10.15 to -14.44 gC hPa$^{0.5}$ kg^{-1} H_2O. The strongest atmospheric sensitivity was observed in 2008 (-14.44 gC hPa$^{0.5}$ kg^{-1} H_2O), whereas comparatively weaker sensitivity occurred in 2014 (-10.15 gC hPa$^{0.5}$ kg^{-1} H_2O). The ISBA-A-g_s simulations closely reproduced the interannual variability, with simulated slopes differing marginally (within ± 0.36 gC hPa$^{0.5}$ kg^{-1} H_2O) from observations. Slight underestimation of slope magnitude was evident in 2006 and 2012, whereas 2014 showed a small overestimation. Overall, ISBA-A-g_s successfully captured the coupling between carbon assimilation and atmospheric demand during peak canopy development. At Ind-IITH, slope magnitudes were generally stronger than those observed at FR-Lam, particularly during the winter season. Under CFI-Monsoon conditions, the observed slope was recorded as -12.92 gC hPa$^{0.5}$ kg^{-1} H_2O, while AFI-Monsoon exhibited a stronger response (-13.85 gC hPa$^{0.5}$ kg^{-1} H_2O), suggesting enhanced atmospheric control under AFI. During winter, the slopes intensified further, reached to -15.28 gC hPa$^{0.5}$ kg^{-1} H_2O under AFI. The ISBA-A-g_s simulations reproduced these seasonal and treatment contrasts (within ± 0.74 gC hPa$^{0.5}$ kg^{-1} H_2O), although a slight underestimation of magnitude was observed under AFI. Comparatively, the stronger slopes at Ind-IITH indicate a greater sensitivity of carbon-water coupling to atmospheric demand in the semi-arid tropical environment relative to the temperate FR-Lam site. Overall, the close agreement between observed and simulated slopes across both sites demonstrates the robustness of ISBA-A-g_s in~~

~~representing the atmospheric regulation of carbon-water interactions under contrasting hydro-climatic regimes.~~



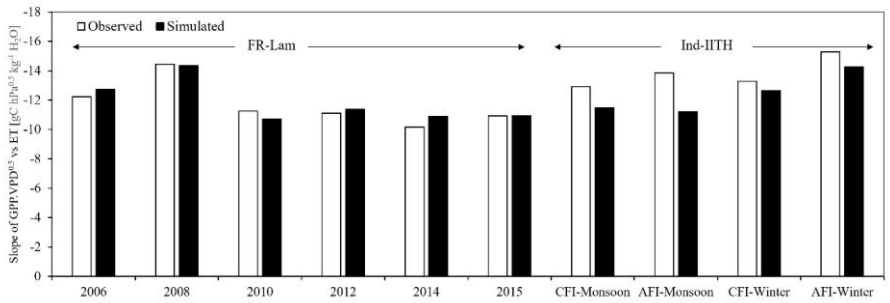


Figure 10. Seasonal variability in the underlying water use efficiency (uWUE) versus ET relationship at the FR-Lam and Ind-IITH sites. Solid bars represent observed EC estimates, while hatched bars denote ISBA-A-g_s simulated values. ~~Seasonal variability in the slope of the GPP.VPD$^{0.5}$ versus ET relationship at the FR-Lam and Ind-IITH sites. Solid bars represent observed EC estimates, while hatched bars denote ISBA-A-g_s simulated values~~.

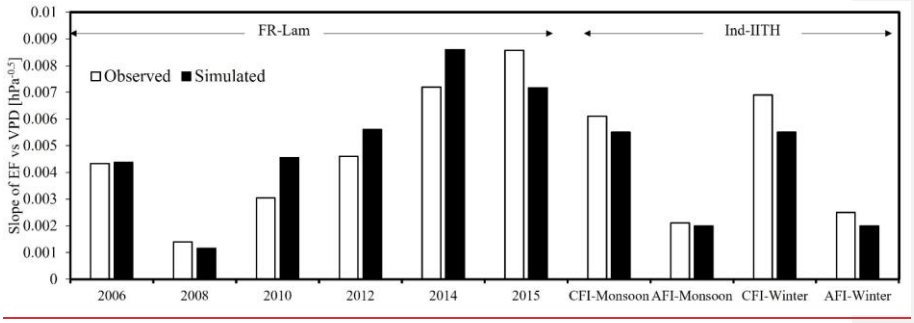
The slope of the evaporative fraction (EF)-VPD relationship, which reflects the ecosystem-scale response of surface energy partitioning to atmospheric demand, is presented in Figure 11. At FR-Lam, observed EF-VPD slopes ranged from 0.0043 hPa$^{-0.5}$ in 2006 to 0.0086 hPa$^{-0.5}$ in 2015, with intermediate values in 2012 (0.0046 hPa$^{-0.5}$) and 2014 (0.0072 hPa$^{-0.5}$), corresponding to contrasting climatic conditions. The ISBA-A-g_s model closely

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reproduced this interannual variability, with simulated slopes differing by only 0.001-0.0015 $hPa^{-0.5}$ from observations. At Ind-IITH, EF-VPD slopes were consistently higher under CFI than AFI during both the monsoon (0.0061 vs. 0.0021 $hPa^{-0.5}$) and winter (0.0069 vs. 0.0025 $hPa^{-0.5}$), representing a 60-65% reduction under AFI and indicating weaker land-atmosphere coupling under partial soil wetting. The ISBA-A-g_s model successfully reproduced these seasonal and treatment-dependent differences, with only slight underestimation of the slope under winter CFI conditions. Overall, the positive EF-VPD slopes confirm the dominant influence of VPD on surface energy partitioning during peak canopy development. The higher slopes observed during the wetter years at FR-Lam and under CFI at Ind-IITH indicate stronger land-atmosphere coupling under moisture-sufficient conditions, whereas the reduced slopes under AFI reflect a moderated evaporative response associated with partial soil drying. Interestingly, the enhanced EF-VPD slopes observed at the FR-Lam site during 2014-2015 may also be attributed to the change in maize cultivar, which promoted greater canopy development and higher LAI. Overall, the ISBA-A-g_s model successfully reproduced ecosystem carbon-water coupling and surface energy partitioning in response to contrasting irrigation treatments across the two study sites.

~~Figure 11 shows the slope of the evaporative fraction (EF) VPD relationship at both FR-Lam and Ind-IITH sites. This relationship reflects the ecosystem-scale response of surface energy partitioning to atmospheric demand and provides indirect insight into land-atmosphere coupling and stomatal regulation. A steeper slope suggests a stronger sensitivity of latent heat flux to VPD, indicating tighter stomatal or moisture control, whereas a weaker slope may reflect reduced coupling or increased non-stomatal limitations. At FR-Lam, observed slopes ranged from 0.0014 (2008) to 0.0086 (2015), reflecting substantial interannual variability in surface energy partitioning. Moderate slopes were recorded in 2006 (0.0043) and 2012 (0.0046), while enhanced coupling between EF and VPD was evident in 2014 (0.0072) and~

~~2015 (0.0086). The interannual range (0.0072) highlights marked differences in surface moisture availability and evaporative dominance across years. ISBA-A-g_s simulations closely reproduced this variability, with simulated slopes ranging between 0.0012 and 0.0085, and deviations within ± 0.001–0.0015. At Ind-IITH, clear irrigation and seasonal contrasts were observed. Under CFI-Monsoon, the observed slope was 0.0061, whereas under AFI-Monsoon, it decreased markedly to 0.0021, indicating a nearly 65% reduction in EF sensitivity under AFI. A similar contrast was evident during winter, where slopes were 0.0069 under CFI-Winter and only 0.0025 under AFI-Winter, representing a reduction of approximately 60–65% under AFI. These results indicate that CFI enhances the responsiveness of evaporative fraction to increases in VPD, while partial soil wetting under AFI dampens this response. ISBA-A-g_s successfully captured both the magnitude and direction of these treatment-induced contrasts, although slight underestimation occurred under winter CFI conditions (0.001 difference). Overall, the positive EF–VPD slopes confirm that VPD dominates surface energy partitioning during peak-LAI periods. Higher slopes at FR-Lam during 2014–2015 and under CFI treatments at Ind-IITH reflect moisture-sufficient conditions promoting strong coupling between carbon assimilation and evapotranspiration. At FR-Lam, these elevated slopes may also be partly attributed to the change in maize cultivar during 2014–2015, which resulted in enhanced canopy development and higher LAI, thereby influencing ecosystem-scale fluxes. In contrast, reduced slopes under AFI indicate moderated evaporative response due to partial soil drying and regulated surface moisture availability.~~



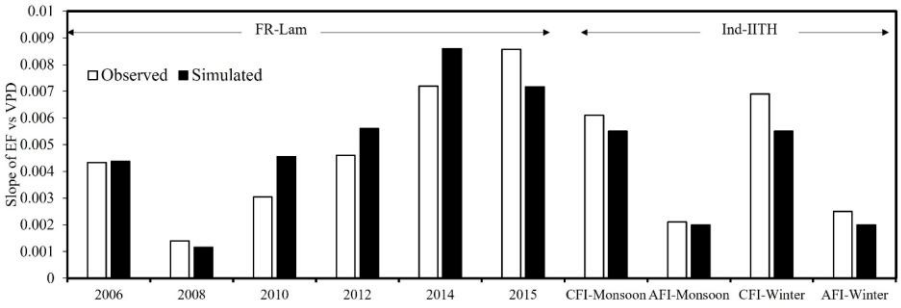


Figure 11. Variability in the slope of the EF vs VPD relationship at the FR-Lam and Ind-IITH sites. Solid bars represent observed EC estimates, and hatched bars denote ISBA-A-g_s simulated values.

4.0 Discussion~~s~~

The calibrated ISBA-A-g_s framework demonstrated robust performance in reproducing the magnitude, variability, and seasonal progression of GPP, ET, and WUE at both the FR-Lam and Ind-IITH sites, ~~confirming~~ demonstrating its ability to represent coupled carbon-water processes across contrasting hydro-climatic ~~regimes~~conditions. The calibrated parameter sets further revealed distinct ecosystem functioning between the two sites. Higher values of GC and D_{Max} at FR-Lam (Table 3) indicate stronger regulation by atmospheric demand, whereas higher values of gm and F2I at Ind-IITH (Table 4) reflect greater sensitivity to irrigation management and soil moisture availability. These contrasting parameter responses are consistent with the differing climatic regimes and water management practices at the two sites, highlighting the

ability of ISBA-A-g_s to realistically represent site-specific ecohydrological processes governing ecosystem carbon assimilation and water use.

At both sites, ISBA-A-g_s better performed in simulating GPP than ET, consistent with previous evaluations of land surface models. This performance difference may reflect the stronger constraints on photosynthetic processes compared with evapotranspiration, which is more sensitive to uncertainties in soil moisture dynamics and surface conductance parameterization (Best et al., 2011; Bonan et al., 2011). The strong agreement in daily and seasonal GPP indicates that the Jacob's-based photosynthesis scheme effectively represents radiation-driven carbon assimilation across varying moisture conditions. In contrast, the larger uncertainties in ET, particularly during years with irregular precipitation (e.g., 2012), highlight the sensitivity of evapotranspiration to soil water stress and land-atmosphere coupling (Dare-Idowu et al., 2021; De Kauwe et al., 2013; Moharana et al., 2025). Consequently, WUE exhibited greater variability because small ET errors propagated into the GPP/ET ratio, consistent with previous studies (Medlyn et al., 2011; Zhou et al., 2014). At the Ind-IITH site, ISBA-A-g_s successfully reproduced carbon assimilation and water fluxes under contrasting irrigation regimes. As at the FR-Lam site, GPP was simulated more accurately than ET, whereas the comparatively lower performance under AFI, particularly for ET during winter, reflects the increased complexity of representing partial root-zone drying, heterogeneous soil moisture distribution, and dynamic stomatal responses under deficit irrigation (Chintala et al., 2026; Chintala and Kambhammettu, 2026; Kang et al., 2001; Tardieu et al., 2015). Consequently, small ET biases propagated into WUE estimates despite the robust simulation of GPP. Importantly, the contrasting responses between CFI and AFI demonstrate that irrigation management can alter the balance between ecosystem carbon assimilation and water loss, thereby driving differences in WUE. Across the temperate FR-Lam and tropical semi-arid Ind-IITH sites, these results indicate that the ability of ISBA-A-g_s to reproduce WUE depends not

only on its representation of photosynthesis and evapotranspiration individually, but also on its capacity to capture their coupled responses to soil moisture availability, atmospheric demand, and irrigation management. Overall, the close agreement between observed and simulated daily, seasonal, and cumulative fluxes across both sites demonstrates that ISBA-A-g_s can reproduce the irrigation-driven carbon-water interactions underlying ecosystem WUE across contrasting hydro-climatic conditions. This highlights the value of a process-based land surface modelling framework for mechanistically evaluating how irrigation strategies modify ecosystem carbon-water coupling rather than simply quantifying their effects on individual carbon or water fluxes. The key scientific contribution of this study is therefore the application of a process-based land surface modelling framework to mechanistically evaluate the effects of contrasting irrigation strategies (CFI and AFI) on ecosystem carbon-water coupling and WUE, and how these effects vary between temperate and tropical semi-arid maize systems.

The consistently steeper uWUE slopes at the Ind-IITH site compared with FR-Lam indicate stronger carbon-water coupling under semi-arid conditions, where elevated VPD and limited soil water availability promote tighter stomatal regulation, resulting in relatively greater carbon gain per unit water loss (Medlyn et al., 2011; Zhou et al., 2014). The higher uWUE observed under AFI is consistent with enhanced intrinsic water use efficiency through partial root-zone drying and root-to-shoot chemical signalling, which reduce transpiration proportionally more than carbon assimilation, as reported in previous deficit-irrigation studies (Kang et al., 2001; Tardieu et al., 2015). In contrast, the higher EF-VPD slopes under CFI indicate stronger land-atmosphere coupling resulting from sustained latent heat flux under adequate soil moisture, whereas the substantially lower slopes under AFI demonstrate that partial soil drying reduced evaporation and transpiration, thereby weakening the sensitivity of surface energy partitioning to atmospheric demand (Seneviratne et al., 2010). Instead of observing these contrasting differences in between sites and irrigation treatments, the calibrated

ISBA-A-g_s captured the underlying physiological processes regulating ecosystem carbon-water interactions across contrasting hydro-climatic conditions. The close agreement between observed and simulated uWUE and EF-VPD relationships further demonstrates that the optimized site-specific parameterizations effectively represent climate-dependent physiological constraints on carbon assimilation, evapotranspiration, and surface energy partitioning.

~~The consistently higher performance for GPP compared to ET aligns with previous evaluations of land surface models, where photosynthetic parameterization is often more constrained than evapotranspiration processes that depend on soil moisture dynamics and surface conductance variability (Best et al., 2011; Bonan et al., 2011). The strong GPP simulations (Figure 6 and 7) across both wet and dry years at FR-Lam suggest that the Jacob's-based photosynthesis scheme within ISBA-A-g_s effectively captures biochemical limitations and radiation-driven assimilation across moisture gradients. However, relatively moderate uncertainties in ET, particularly during years with irregular precipitation distribution (e.g. 2012), indicate sensitivity to soil water stress parameterization and aerodynamic coupling, consistent with findings reported by (Dare Idowu et al., 2021; De Kauwe et al., 2013; Seneviratne et al., 2010). As WUE integrates both carbon gain and water loss, its variability amplifies with small deviations in ET, explaining the comparatively lower R^2 values (Figure 6) observed for WUE during wet years (2014 and 2015). Similar propagation effects have been reported in cropland ecosystems, where ET biases disproportionately affect WUE simulations (Medlyn et al., 2011; Zhou et al., 2014). The pronounced interannual variability in cumulative GPP (~950 to ~1400 g C m^{-2}) and ET (800 – 1150 kg H_2O m^{-2}) at FR-Lam reflects strong climatic regulation of seasonal carbon-water budgets, but also includes cultivar effects (Figure 7). This behaviour is consistent with observations from temperate croplands showing positive GPP anomalies during moist growing seasons (Ciais et al., 2005; Reichstein et al., 2013).~~

Interestingly, increased ET in wet years did not proportionally enhance WUE, indicating that additional water availability stimulated transpiration more strongly than carbon assimilation. Such decoupling between GPP and ET under high evaporative demand has been observed in maize systems where stomatal regulation becomes increasingly responsive to atmospheric VPD rather than soil moisture alone (Kang et al., 2001; Tardieu et al., 2015). The performance of ISBA-A-g_s to reproduce these cumulative trajectories suggests that the model captures seasonal-scale feedbacks between canopy development and atmospheric demand (Figure 7 and 9). At the semi-arid Ind-IITH site, irrigation management introduced an additional layer of control over carbon-water dynamics. The higher cumulative GPP during winter compared to monsoon reflects improved radiation availability and lower cloud cover, which enhanced photosynthetic efficiency despite higher evaporative demand (Figure 9). Similar seasonal contrasts have been reported for tropical and subtropical maize systems, where winter cropping benefits from stable radiation regimes and reduced atmospheric variability (Deb Burman et al., 2024; Lobell et al., 2011). The reduced ET under AFI relative to CFI, particularly during monsoon, indicates partial stomatal regulation and moderated transpiration without proportionally reducing carbon assimilation (Fereres and Soriano, 2007; Kang et al., 2001). Consequently, average WUE was consistently higher under AFI, as observed in previous studies of (Geerts and Raes, 2009; Medrano et al., 2015). ISBA-A-g_s ability to capture this treatment-specific divergence highlights the robustness of its soil moisture stress formulation and canopy resistance parameterization (Figure 8 and 9).

The diagnostic analyses using GPP·$VPD^{0.5}$ ET relationships and EF–VPD responses further demonstrate that the model captures underlying eco-physiological controls beyond statistical agreement (Figure 10). The normalization of GPP by VPD effectively isolates biochemical limitations from atmospheric demand effects (Zhou et al., 2014), so it focuses on plant physiology and should be similar according to the same plant cultivar. So the EF

~~sensitivity to VPD reflects surface energy partitioning regulated by stomatal conductance and soil moisture availability (Seneviratne et al., 2010). Across both sites, steeper cumulative slopes during peak canopy development confirm that LAI-mediated increases in photosynthetic capacity drive mid-season carbon assimilation. The consistency between simulated and observed cumulative patterns suggests that ISBA-A-g_s realistically represents canopy phenology-hydrology interactions, a key requirement for predicting future carbon-water feedbacks under climate variability. Overall, the stronger performance for GPP relative to ET and WUE suggests that while biochemical assimilation processes are well constrained, hydrological components remain more sensitive to meteorological forcing. Given the increasing importance of optimizing irrigation under climate change, accurate representation of ET partitioning and stomatal regulation is critical for reliable WUE projections. The demonstrated capability of ISBA-A-g_s to reproduce interannual variability in ET and soil moisture contrasts, and cumulative seasonal budgets across temperate (FR-Lam) and tropical semi-arid (Ind-IITH) agro-ecosystems indicates strong potential for its application in climate-resilient water resources planning and carbon-water management strategies.~~

5.0 Model limitations and Future scope

Despite its robust performance, several limitations should be acknowledged. First, LAI was prescribed at 10-day intervals, which may be insufficient to capture the rapid canopy development and phenological transitions of maize, thereby introducing uncertainties in the simulation of ecosystem fluxes. Second, model calibration employed a one-at-a-time parameter optimization approach which, although computationally efficient, does not account for nonlinear interactions among model parameters. Third, the Ind-IITH analysis was based on a single agricultural year comprising monsoon and winter seasons under CFI and AFI treatments. Although this dataset encompasses a broad range of hydro-meteorological and irrigation

conditions, it does not permit the assessment of interannual variability or independent model validation. Consequently, the findings for the Ind-IITH site should be interpreted within the scope of the available observations rather than as evidence of long-term model transferability across tropical semi-arid environments. Finally, contrasting hydro-climatic conditions across seasons (monsoon versus winter in India and wet versus dry years in France) introduce additional uncertainty in parameter transferability by altering radiation, VPD, and soil moisture regimes. Given that this study represents an initial evaluation, future research should assess the ISBA-A-g_s model using multi-year observations across diverse hydro-climatic conditions and irrigation management scenarios to better quantify interannual variability, parameter robustness, and long-term model transferability. In addition, incorporating higher-frequency vegetation dynamics (e.g., sub-weekly LAI and phenological updates) together with advanced global optimization techniques (e.g., Monte Carlo or Bayesian calibration) would improve the representation of parameter interactions, reduce calibration uncertainty, and further enhance simulations of coupled carbon-water processes in maize agroecosystems.

~~In the current configuration, LAI was prescribed at 10-day intervals. Such temporal aggregation may be insufficient for fast-growing crops like maize, where rapid phenological development and canopy expansion occur within shorter timescales (< 10 days). Consequently, micro-physiological responses and short-term canopy dynamics may be masked within these averaged inputs, potentially contributing to the observed overestimation of fluxes during peak growth stages. Further, the model calibration was performed using a "one-at-a-time" parameter optimization approach. While computationally efficient, this method neglects potential interactive and nonlinear effects among parameters. Finally, the seasonal climatic variability posed a significant challenge for parameter transferability. Contrasting hydro-climatic conditions across maize growing seasons (monsoon vs. winter in India; wet vs. dry seasons in France) influence radiation regimes, VPD dynamics, and soil moisture availability. These~~

~~variations propagate uncertainty during calibration and may partly explain mismatches between observed and simulated datasets.~~

~~This study represents the first application of a locally calibrated ISBA model in its MEB configuration to simulate GPP, ET, and WUE of maize in a tropical semi-arid Indian agro-ecosystem. Since WUE is a critical eco-hydrological indicator, this study advances the quantitative understanding of WUE variability under contrasting hydro-climatic conditions and irrigation regimes. The successful adaptation and validation of the ISBA-A-g_s model establishes a robust foundation for process-based agro-hydrological assessments. The calibrated model can be further utilized to detect water stress conditions to investigate the response of evapotranspiration to varying climatic demand. Future, incorporating higher temporal resolution vegetation dynamics (e.g., LAI and phenology updates at sub-weekly scales), employing multi-parameter or global optimization techniques (e.g., Monte Carlo, Bayesian calibration) to capture nonlinear parameter interactions can further improve the model accuracy. Further, the expanding simulations across multiple growing seasons and diverse irrigation/management scenarios to enhance model robustness.~~

6.0 Conclusions

This study investigated the ecosystem-scale dynamics of GPP, ET, and WUE of maize under contrasting hydro-climatic conditions in a temperate (FR-Lam, France) and a tropical semi-arid (Ind-IITH, India) ecosystems using the ISBA-A-g_s SVAT model within the SURFEX land surface modelling framework. Driven by in-situ meteorological observations and measured vegetation characteristics, the model was calibrated and validated to simulate seasonal carbon-water fluxes. The major findings are summarized as follows:

1. At FR-Lam, interannual climatic variability primarily regulated GPP, ET, and WUE, whereas irrigation management exerted a stronger control on ecosystem functioning at Ind-IITH by substantially reducing ET while maintaining relatively stable carbon assimilation.
2. The calibrated parameter sets revealed that mesophyll conductance, stomatal regulation, atmospheric demand, and soil moisture limitation differed systematically between climates and irrigation treatments, demonstrating that site-specific calibration enables ISBA-A-g_s to mechanistically represent ecosystem responses.
3. The calibrated ISBA-A-g_s model consistently achieved higher performance for GPP than ET while realistically capturing the contrasting influences of climate variability and irrigation management on ecosystem carbon and water fluxes, demonstrating its capability under the hydro-climatic and management conditions.
4. The complementary uWUE and EF-VPD diagnostic analyses demonstrated that ISBA-A-g_s captures the ecophysiological and hydrological mechanisms governing ecosystem carbon-water interactions and land-atmosphere coupling processes.

Overall, this study demonstrates that ISBA-A-g_s provides a robust process-based framework for representing ecosystem carbon-water interactions under contrasting temperate (FR-Lam) and tropical semi-arid (Ind-IITH) hydro-climatic conditions. While the model successfully reproduced interannual variability at FR-Lam and seasonal irrigation-driven responses at Ind-IITH, the conclusions for the latter are restricted to the available observation period and should be interpreted as evidence of the model's capability under the evaluated irrigation and seasonal conditions alone.

~~This study aimed to investigate ecosystem-scale GPP, ET, and WUE dynamics of maize grown under two contrasting hydro-climatic conditions: temperate (FR-Lam, France) and tropical semi-arid (Ind-IITH, India), using the ISBA-A-g_s SVAT model within the SURFEX land surface modelling framework. The model was driven by in-situ meteorological~~

measurements, along with observed vegetation variables, and was subsequently calibrated and validated to simulate seasonal variations in GPP, ET, and WUE. The key findings of this study are summarized as follows:

1. This study presents the first application of the MEB configuration of the ISBA-A-g_s land surface model to quantify ecosystem-scale GPP, ET, and WUE dynamics in both temperate (FR-Lam) and semi-arid Indian (Ind-IITH) agro-ecosystems, addressing a critical observational and modelling gap.
2. This study provides site-specific calibrated biogeochemical parameters for maize in semi-arid India, offering a robust foundation for improved regional-scale simulations of carbon-water interactions and WUE dynamics.
3. The calibrated ISBA-A-g_s model reliably reproduced ecosystem-scale GPP and ET fluxes under both temperate (FR-Lam) and tropical semi-arid (Ind-IITH) conditions, demonstrating strong transferability across contrasting hydro-climatic regimes.
4. At the FR-Lam site, GPP was simulated with high accuracy (R^2 of 0.80 to 0.93), whereas ET and WUE showed greater sensitivity to meteorological variability, emphasizing the inherent complexity and atmospheric dependence of hydrological processes.
5. At the Ind-IITH site, ISBA-A-g_s consistently reproduced GPP more robustly, followed by ET and WUE, with AFI treatment introducing additional variability in simulated ET fluxes. The model's ability to resolve irrigation-specific divergence between CFI and AFI treatments underscores the strength of its soil moisture stress representation and canopy resistance parameterization.
6. ISBA-A-g_s effectively captured both interannual variability and irrigation-induced contrasts, with simulated GPP·$VPD^{0.5}$·ET slopes closely aligning with observations (within ± 0.36 gC $hPa^{0.5}$ kg^{-1} H_2O (FR-Lam) and ± 0.74 gC $hPa^{0.5}$ kg^{-1} H_2O (Ind-IITH)), confirming its ability to represent atmospheric regulation of carbon-water coupling.

~~The demonstrated ability of the ISBA-A-g_s model to reproduce interannual variability, irrigation effects, and cumulative seasonal carbon-water budgets across temperate (FR-Lam) and tropical semi-arid (Ind-IITH) agro-ecosystems underscores its strong potential for application in climate-resilient irrigation management and carbon-water optimization strategies.~~

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Credit authorship contribution statement

Syam Chintala: Experimentation, Data collection and curation, Methodology, Model setup simulations, Results Analysis, Investigation, Writing - Original draft. **Lionel Jarlan:** Results analysis, Writing - Original draft & editing, Project administration, Supervision. **Vincent Rivalland:** Results Analysis and interpretation, and Writing - Original draft & review. **Aaron Boone:** Results analysis and Model setup. **Oluwakemi Dare-Idowu:** Data curation and Input

data preparation. **Valerie Le Dantec:** Results interpretation and Writing - Original draft & review. **Gilles Boulet**: Results interpretation and Writing - Original draft & review. **BVN P Kambhammettu**: Results analysis, Writing - Original draft & review, Project administration, Supervision. **Aurore Brut**: Results analysis, Writing - Original draft & review, Project administration, Supervision.

Code/Data availability statement

Relevant Codes and Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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