An improved approach of winter wheat yield estimation by jointly assimilating remotely sensed leaf area index and soil moisture into the WOFOST model

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1. Ensemble Kalman Filter

For the implementation of the EnKF, we based on our previous research of Huang et al. (2016) and Zhuo et al. (2022). The core part of the EnKF is the calculation of the Kalman gain matrix,

$$y = Hx_t + \varepsilon \tag{1}$$

$$x_t = Ax_{t-1} + \nu \tag{2}$$

Where y is the observation vector, ε and ν are Gaussian random error vector with a mean of zero, and H is the observation operator related to y, it can be taken as an identity matrix in this study. A represents a state-transition model that links x_t and x_{t-1}, in the CDMA system it represents crop model. And the forecast of x_t at t=k is Gaussian with mean $x^f_{t=k}$ and error covariance $P^f_{t=k}$ can be calculated as Eqs. (3) – (4):

$$x^a_{t=k} = x^f_{t=k} + K(y - Hx^f_{t=k}) \tag{3}$$

$$P^a_{t=k} = (I - KH)P^f_{t=k} \tag{4}$$

Where f and a are indices of the prior and posterior estimates, respectively, I is the identity matrix, and K is the Kalman gain matrix defined as Eq. (5)

$$K = P^f_{t=k}H^T(HP^f_{t=k}H^T + R)^{-1} \tag{5}$$

When solving the Kalman gain, Houtekamer and Mitchell (2001) suggest calculating $P^f_{t=k}H^T$ and $HP^f_{t=k}H^T$ directly from the ensemble members, rather than calculating each element of Eq. (5):

$$P^f H^T = (N_e - 1)^{-1} \sum_{n=1}^{N_e} (x_n^f - \bar{x}^f)(Hx_n^f - H\bar{x}^f)^T \quad (6)$$

$$HP^f H^T = (N_e - 1)^{-1} \sum_{n=1}^{N_e} (Hx_n^f - H\bar{x}^f)(Hx_n^f - H\bar{x}^f)^T \quad (7)$$

Where N_e is the number of ensemble members, n is a running index for ensemble member, and $\bar{x}^f$ represents the ensemble mean calculated as Eq. (8).

$$\bar{x}^f = N_e^{-1} \sum_{n=1}^{N_e} x_n^f \quad (8)$$

$$H\bar{x}^f = N_e^{-1} \sum_{n=1}^{N_e} Hx_n^f \quad (9)$$

2. Supplementary Figures

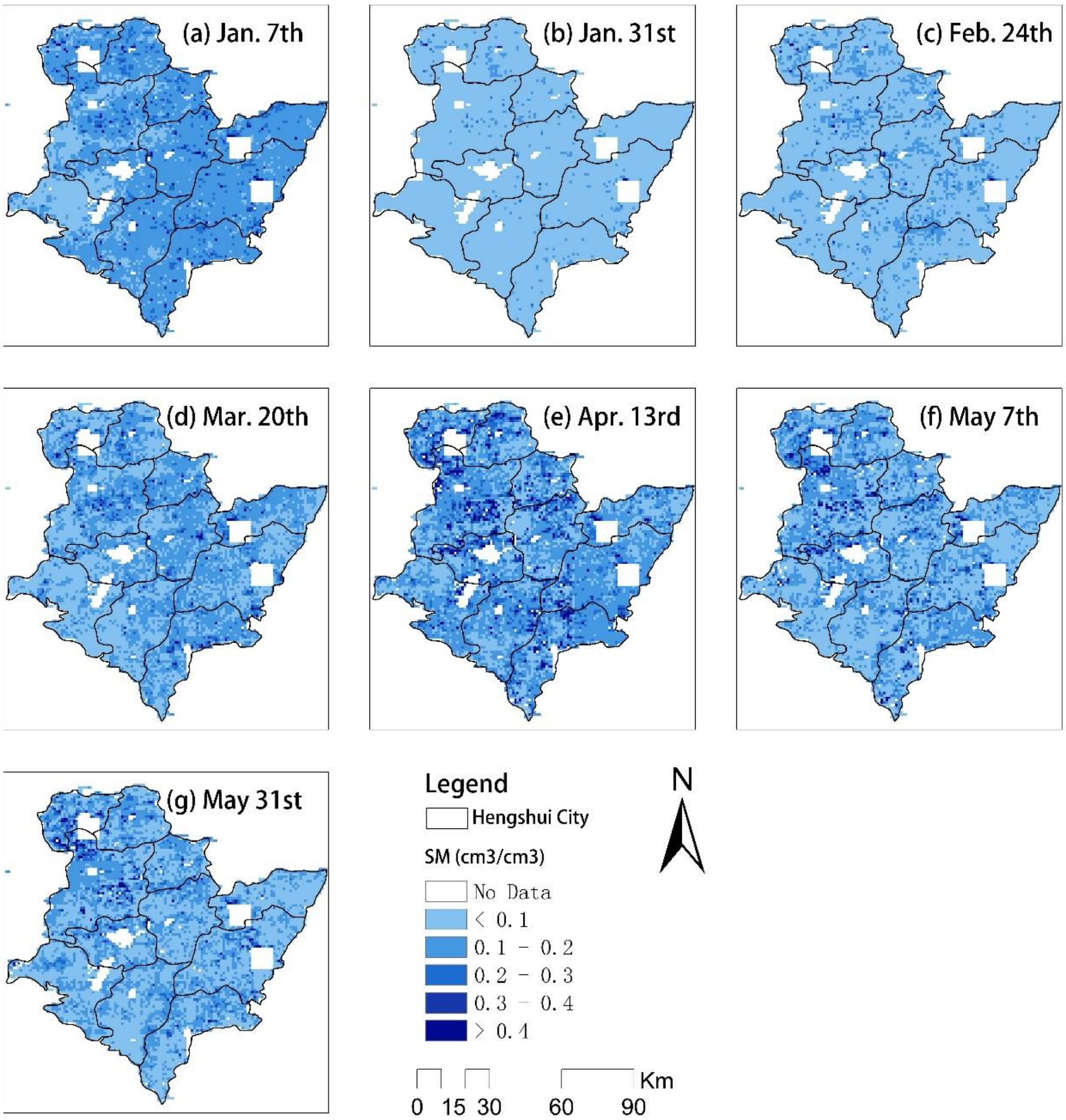


Figure S1. SM_{SMAP} images of Hengshui city in 2017 during winter wheat growing season

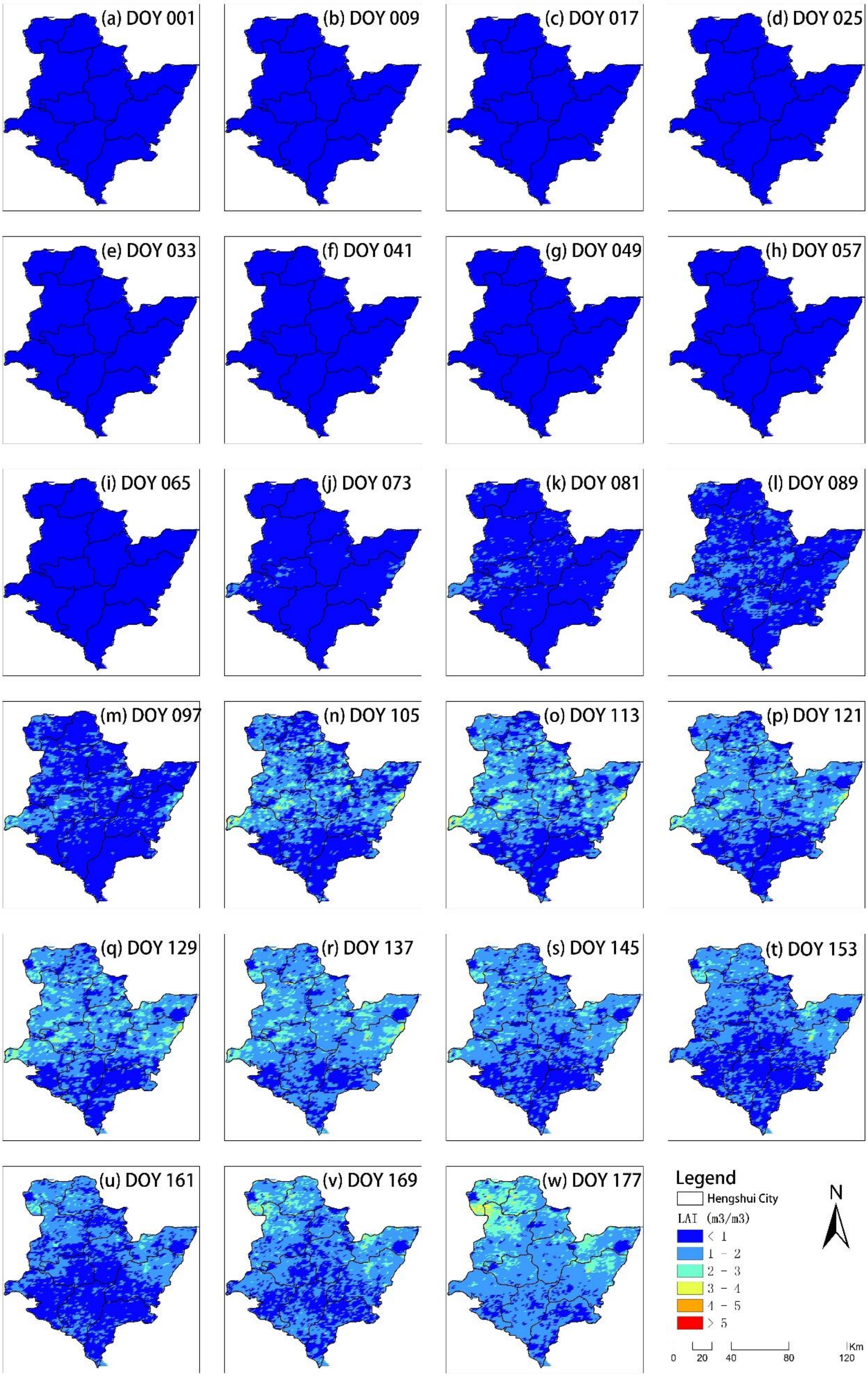


Figure S2. LAI_{MODIS} images of Hengshui city in 2017 during winter wheat growing season

The fitting results of LAI and NDVI are shown as formula (1):

$$LAI = -1/0.304 * \ln\left[(0.901 - NDVI)/0.717\right] \quad (1)$$

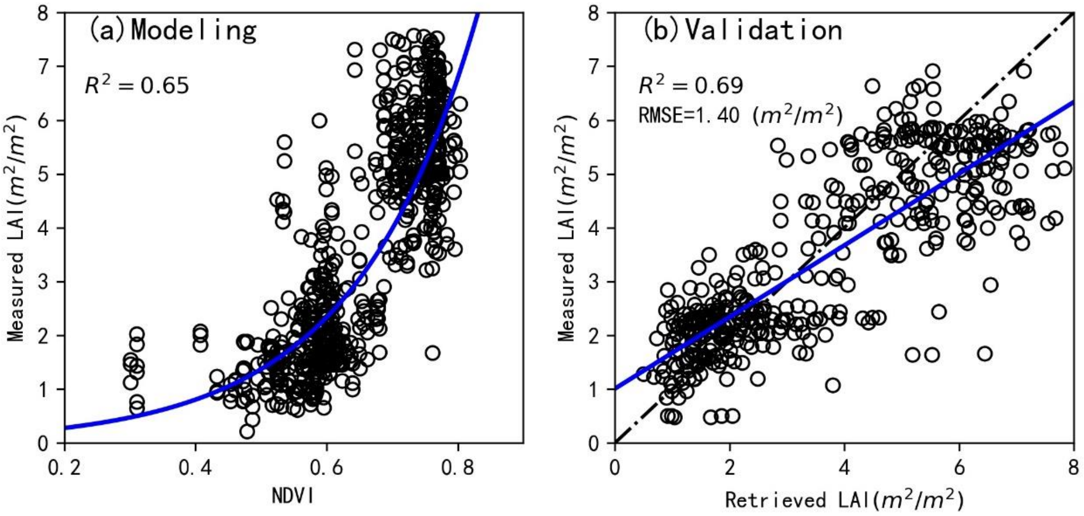


Figure S3. (a) Modeling of measured LAI and NDVI (b) Validation of retrieved LAI results

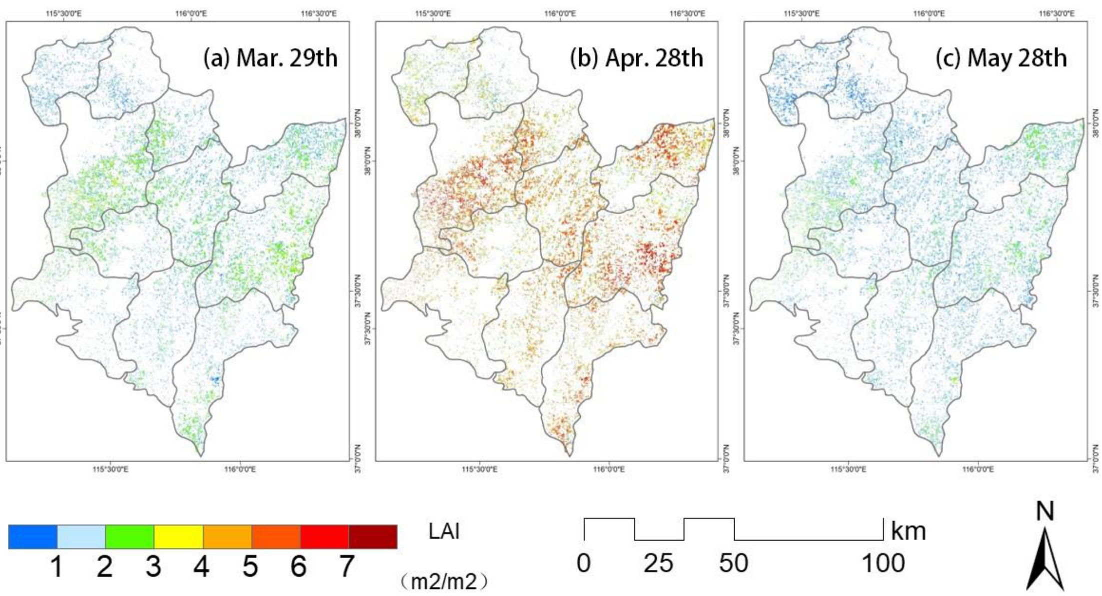
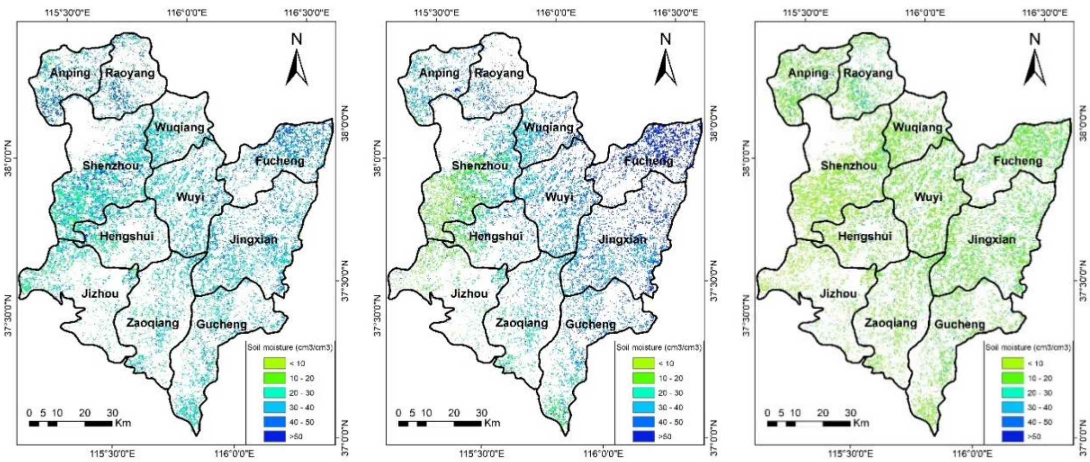


Figure S4. LAI_{S2} images of Hengshui city in 2017 during winter wheat growing season



(a) Apr 1st (b) May 7th (c) Jun 1st

Figure S5. Maps of SM in the study area retrieved from the water cloud model (a) 1 April, (b) 7 May and (c) 1 Jun. (Zhuo et al., 2019)

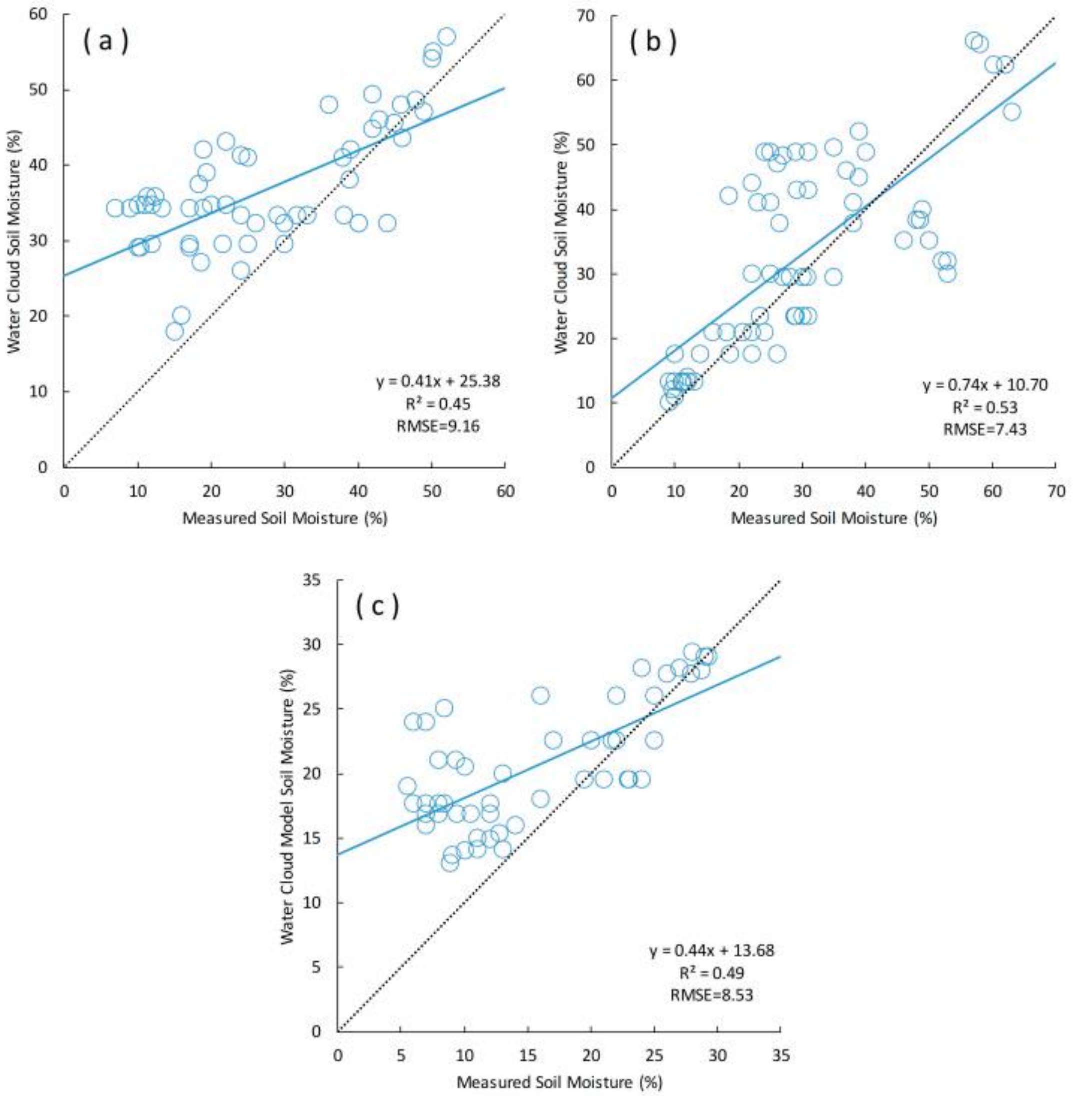


Figure S6. Validation of the retrieved SM from the water cloud model (Zhuo et al., 2019)

References

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