This supplementary material consists of equations of tables and prediction results in the paper and in the following sections. Section S1 is the parameterization scheme. Sections S2, S3, and S13 present the evaluation metrics calculated over the entire study period for continuous observations, 3-day observation intervals, and random observation intervals, respectively. Sections S4-S12 provide the results for scenarios with observation intervals of five and seven days, together with their corresponding evaluation metrics.

S1 Parameterization Scheme

Table S1. The selected scheme of Noah-MP parameterizations.

Parameterizations Description	Scheme selected
DYNAMIC_VEG_OPTION	7: off (use input LAI and FVEG)
CANOPY_STOMATAL_RESISTANCE_OPTION	1: Ball-Berry
BTR_OPTION	2: CLM (matric potential)
SURFACE_RUNOFF_OPTION	1: TOPMODEL with groundwater
SUBSURFACE_RUNOFF_OPTION	1: TOPMODEL with groundwater
SURFACE_DRAG_OPTION	1: M-O
SUPERCOOLED_WATER_OPTION	1: no iteration
FROZEN_SOIL_OPTION	1: linear effects, more permeable
RADIATIVE_TRANSFER_OPTION	3: two-stream applied to vegetated fraction
SNOW_ALBEDO_OPTION	2: CLASS
PCP_PARTITION_OPTION	2: BATS
TBOT_OPTION	2: TBOT at ZBOT (8 m) read from a file
TEMP_TIME_SCHEME_OPTION	2: full implicit
SURFACE_RESISTANCE_OPTION	1: Sakaguchi09
GLACIER_OPTION	1: include phase change of ice
DVIC_INFILTRATION_OPTION	1: Philip scheme
SNOW_THERMAL_CONDUCTIVITY	1: Stieglitz (Yen,1965) scheme
SOIL_DATA_OPTION	1: use input dominant soil texture
PEDOTRANSFER_OPTION	1: Saxton and Rawls (2006)

CROP_OPTION	0: No irrigation
IRRIGATION_METHOD	0: method based on geo_em fractions

S2 Continuous observations

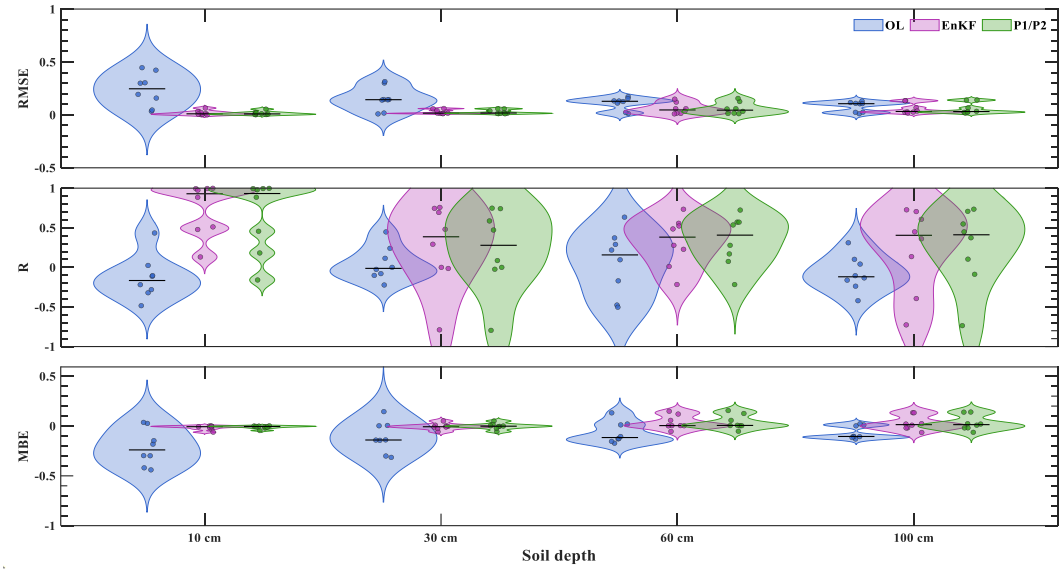

Figure S1. Comparison of RMSE, MBE, and R for OL simulations and two assimilation strategies across four soil layers at eight sites over the entire time period under continuous observations.

S3 3-day observation interval

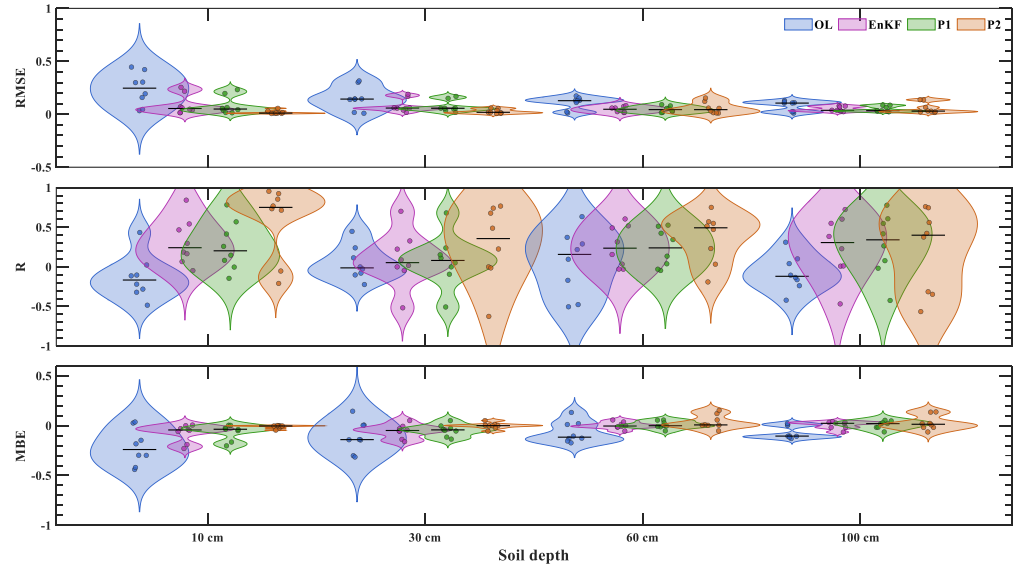

Figure S2. Comparison of RMSE, MBE, and R for OL simulations and three assimilation strategies across four soil layers at eight sites over the entire time period with an observation interval of 3 days.

S4 5-day observation interval

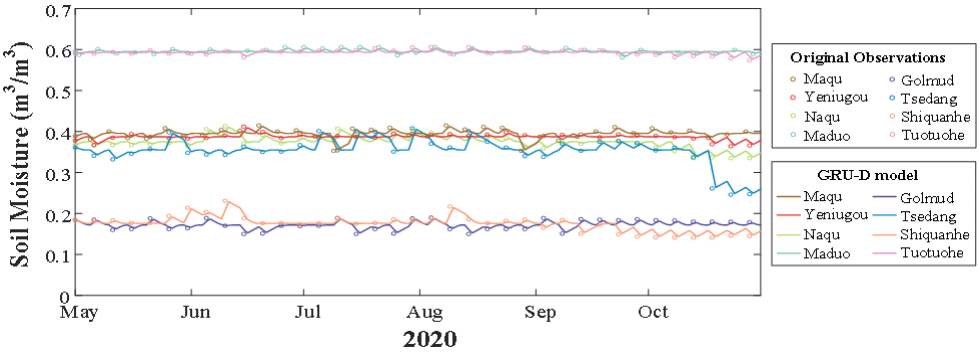

Figure S3. Comparison between original SM observations and the GRU-D reconstructed series. Dots represent original observations, and the solid line denotes the imputed time series by the GRU-D model.

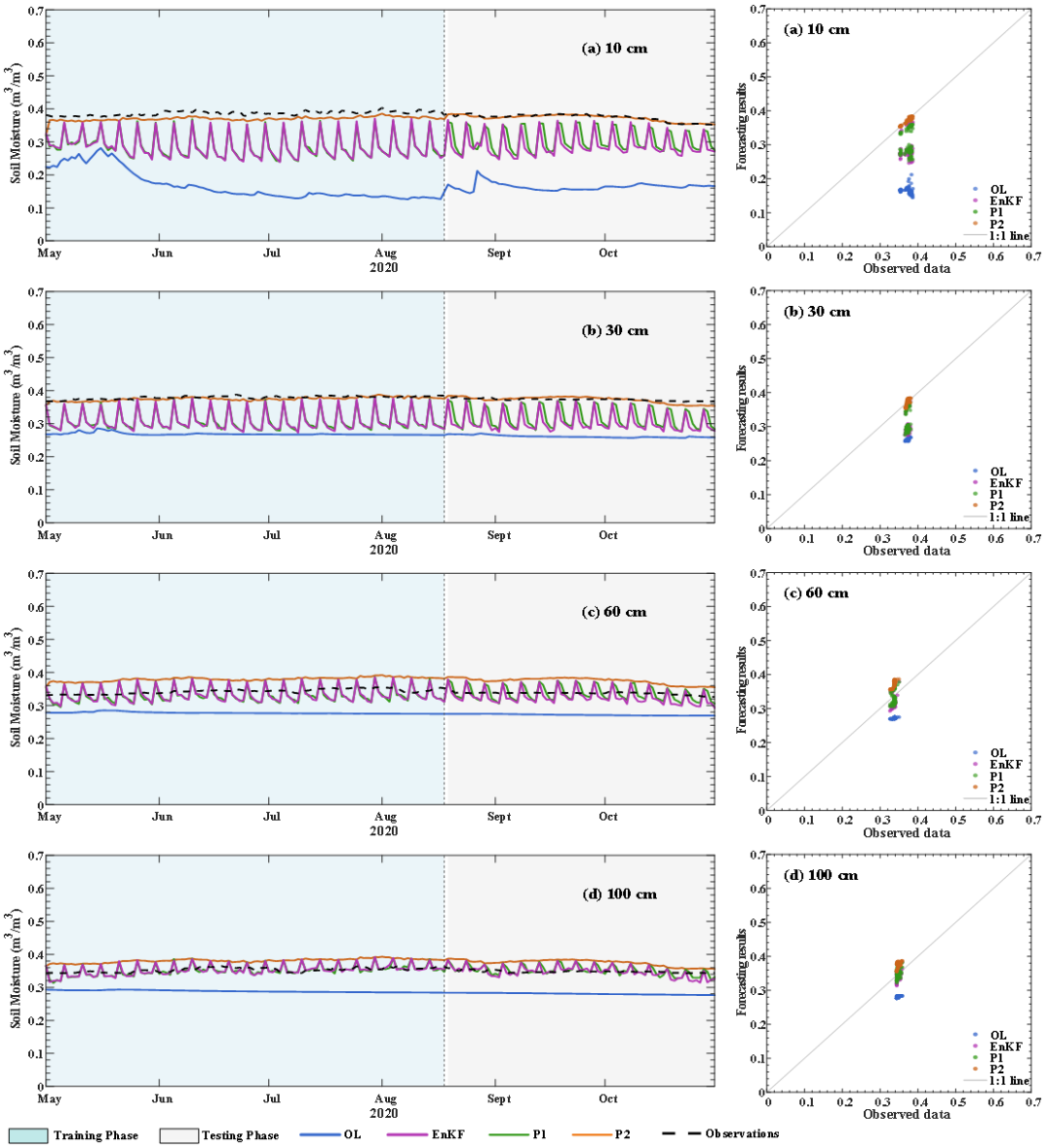

Figure S4. Averaged daily SM time series (left panels) and scatter plots (right panels) across the eight study sites for OL, EnKF, P1, P2, and observations under the 5-day observation interval scenario. Panels (a)-(d) correspond to soil depths of 10, 30, 60, and 100 cm, respectively. The gray solid line denotes the 1:1 reference line.

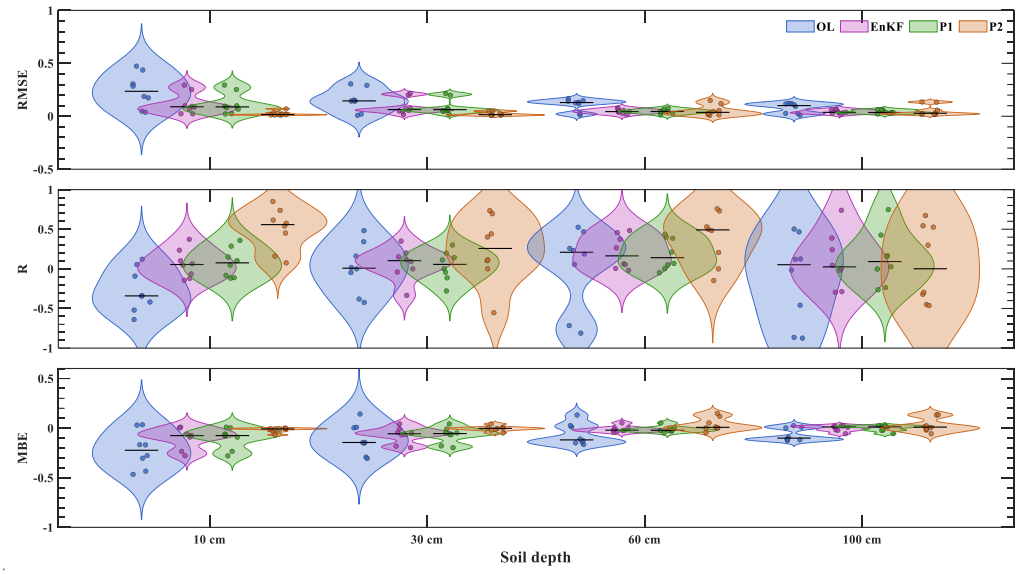

Figure S5. Comparison of RMSE, MBE, and R for OL simulations and three assimilation strategies across four soil layers at eight sites during the training phase with an observation interval of 5 days.

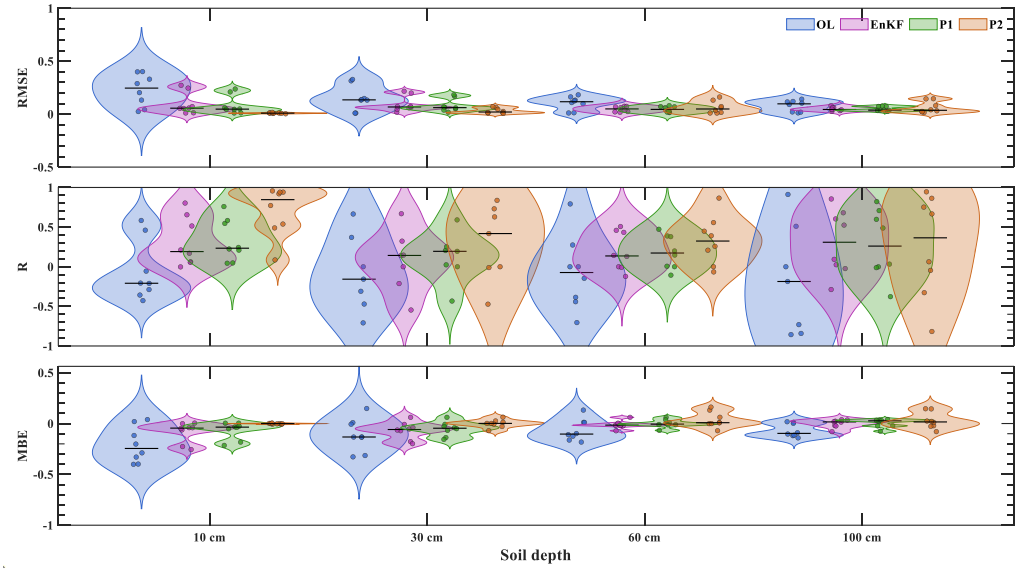

Figure S6. Comparison of RMSE, MBE, and R for OL simulations and three assimilation strategies across four soil layers at eight sites over the entire time period with an observation interval of 5 days.

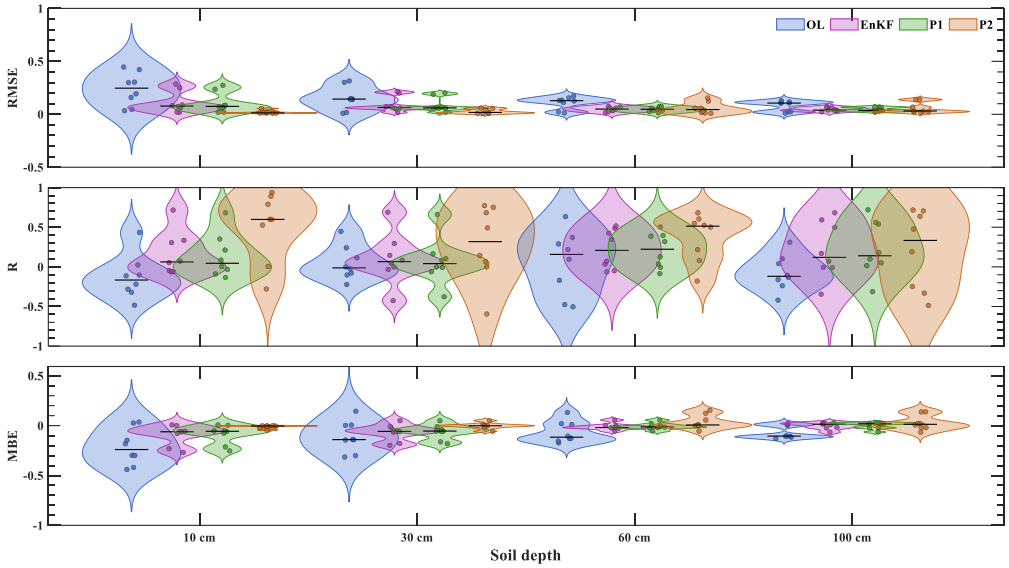

Figure S7. Comparison of RMSE, MBE, and R for OL simulations and three assimilation strategies across four soil layers at eight sites over the entire time period with an observation interval of 5 days.

Table S2. Average runtime of the three data assimilation schemes.

EnKF	P1	P2
275.64 s	180.69 s	191.13 s

S5 7-day observation interval

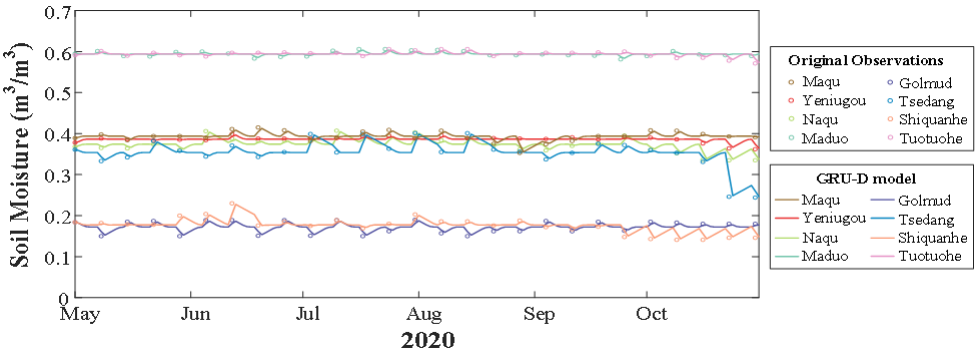

Figure S8. Comparison between original SM observations and the GRU-D reconstructed series under a 7-day observation interval. Dots represent original observations, and the solid line denotes the imputed time series by the GRU-D model.

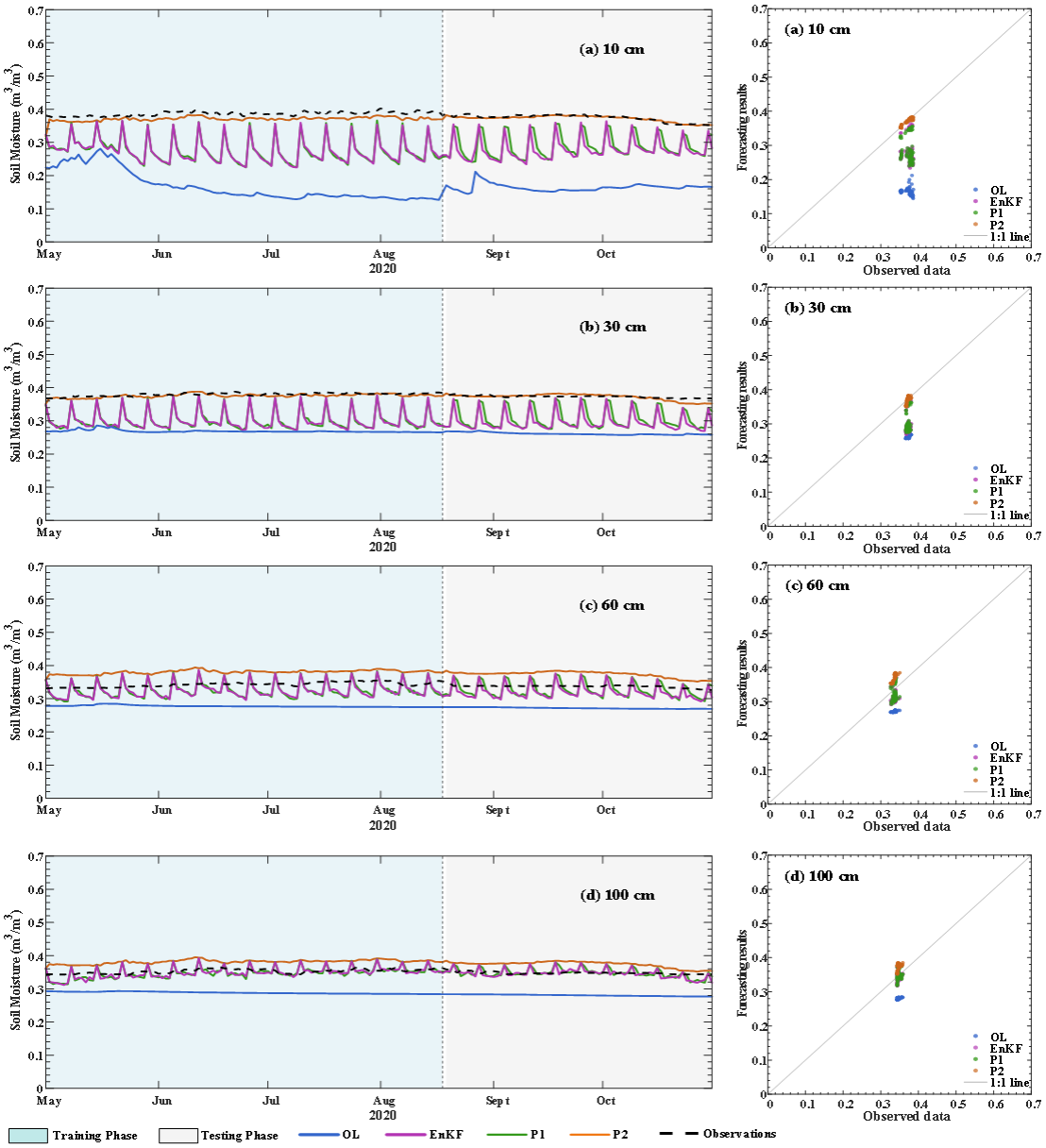

Figure S9. Averaged daily SM time series (left panels) and scatter plots (right panels) across the eight study sites for OL, EnKF, P1, P2, and observations under the 7-day observation interval scenario. Panels (a)-(d) correspond to soil depths of 10, 30, 60, and 100 cm, respectively. The gray solid line denotes the 1:1 reference line.

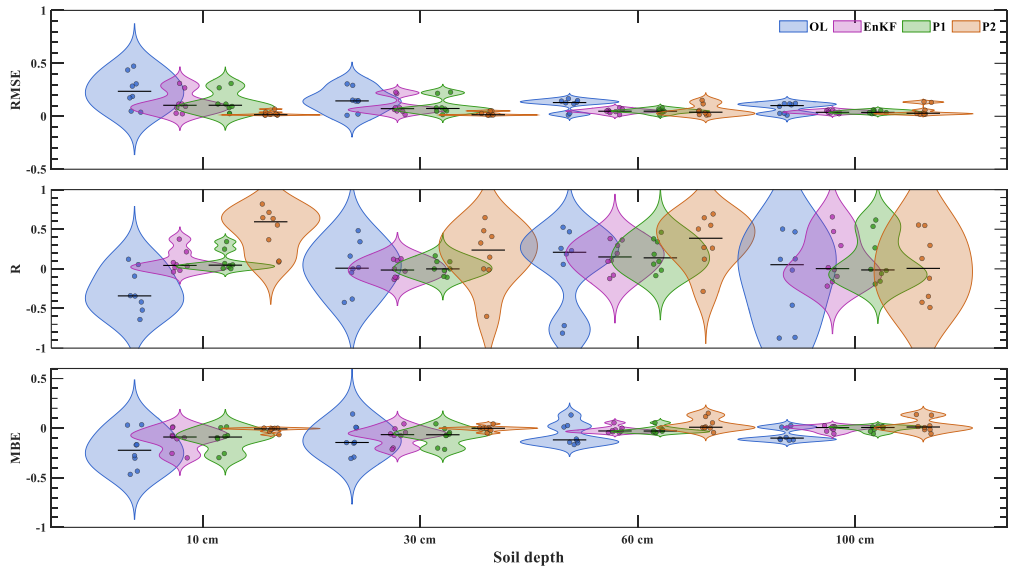

Figure S10. Comparison of RMSE, MBE, and R for OL simulations and three assimilation strategies across four soil layers at eight sites during the training phase with an observation interval of 7 days.

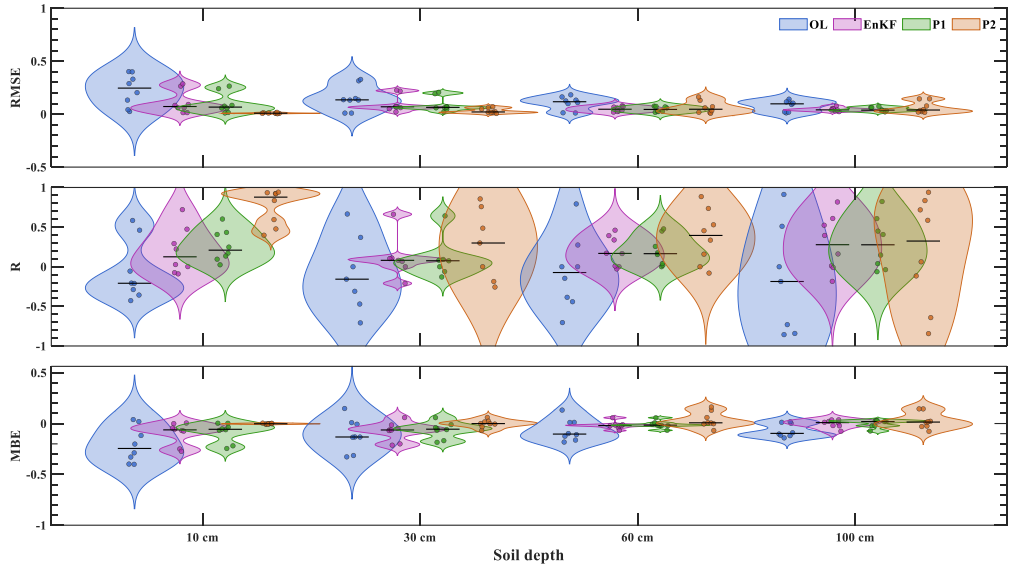

Figure S11. Comparison of RMSE, MBE, and R for OL simulations and three assimilation strategies across four soil layers at eight sites during the testing phase with an observation interval of 7 days.

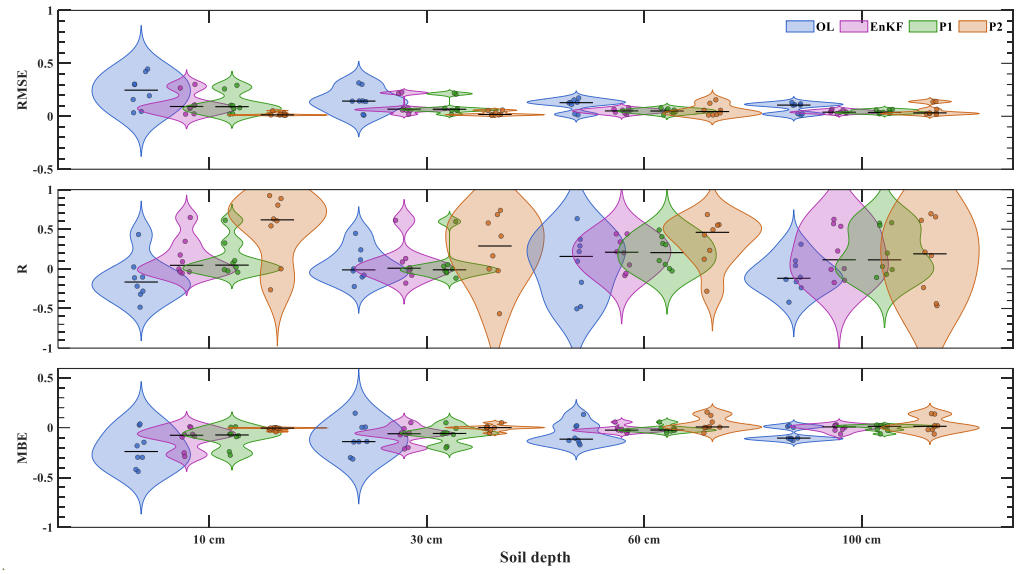

Figure S12. Comparison of RMSE, MBE, and R for OL simulations and three assimilation strategies across four soil layers at eight sites over the entire time period with an observation interval of 7 days.

Table S3. Average runtime of the three data assimilation schemes.

EnKF	P1	P2
278.04 s	184.61 s	191.80 s

S6 Random observation intervals

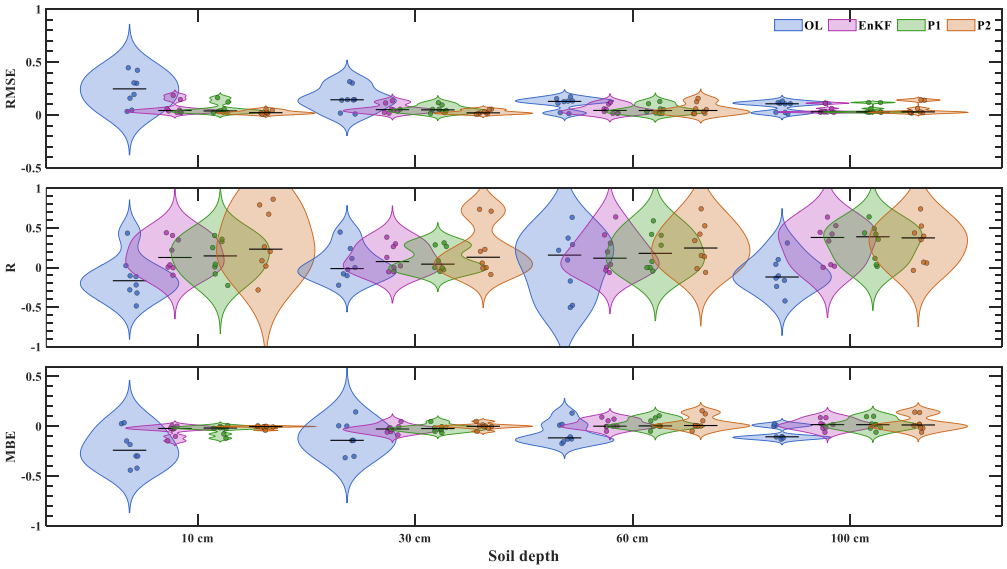

Figure S13. Comparison of RMSE, MBE, and R for OL simulations and three assimilation strategies across four soil layers at eight sites over the entire time period with randomized observation intervals.