



Supplement of

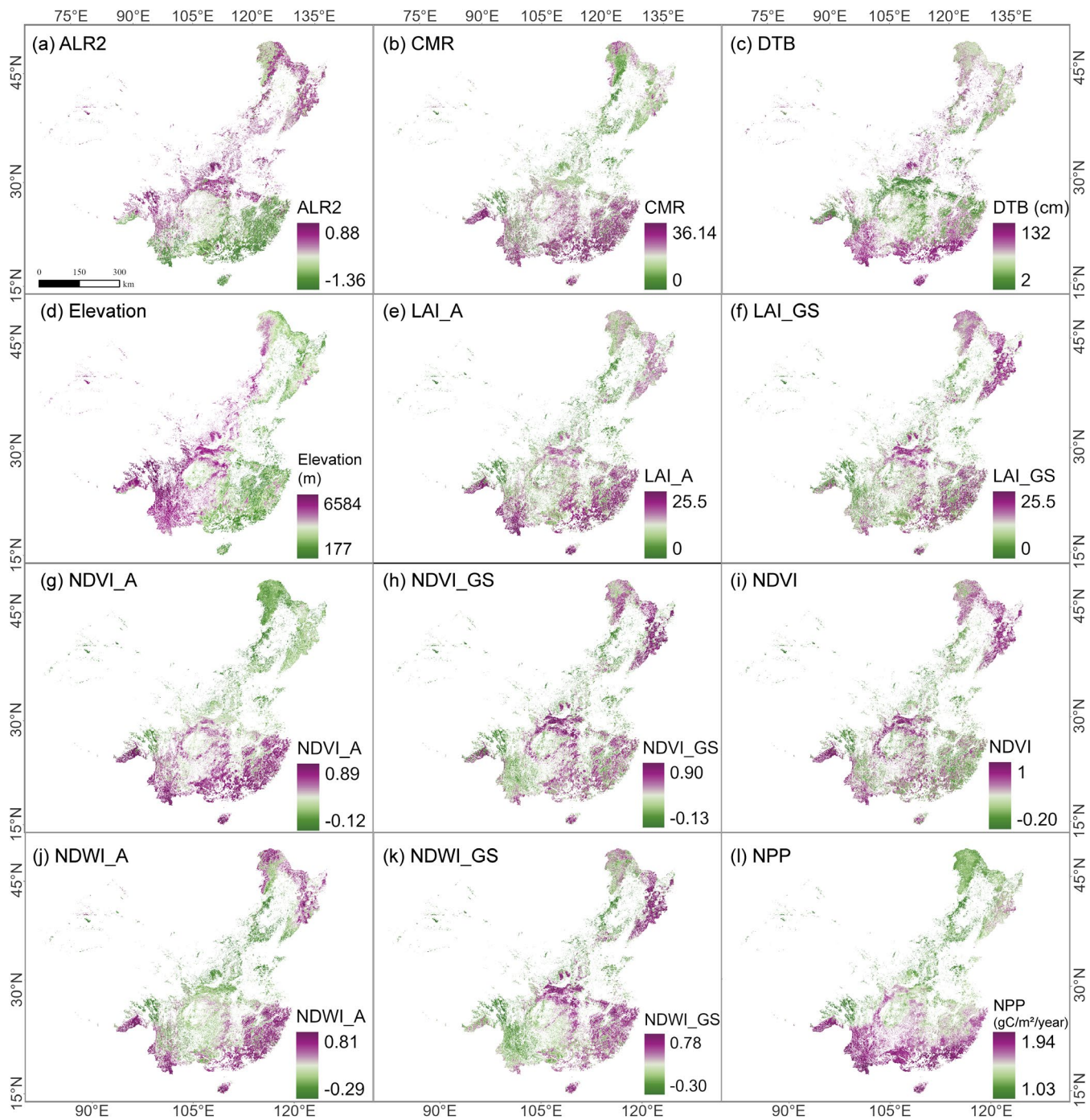
High-resolution, multi-depth mapping of soil bulk density and pH in China's forests using machine learning

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S1 Supplementary Figures



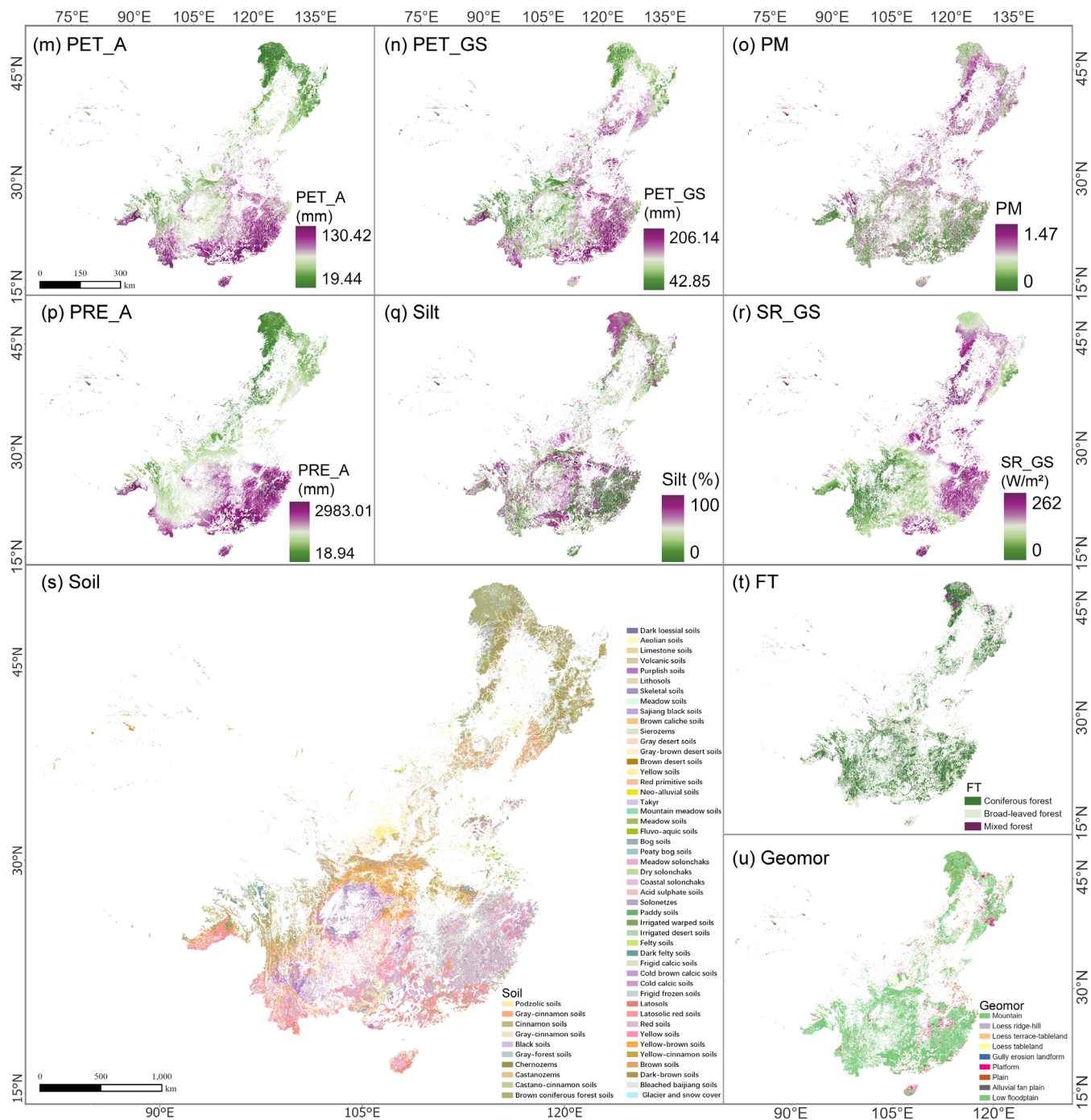


Figure S1. Spatial Distribution of Covariates Selected by Feature Ranking and Selection (FRFS) method.

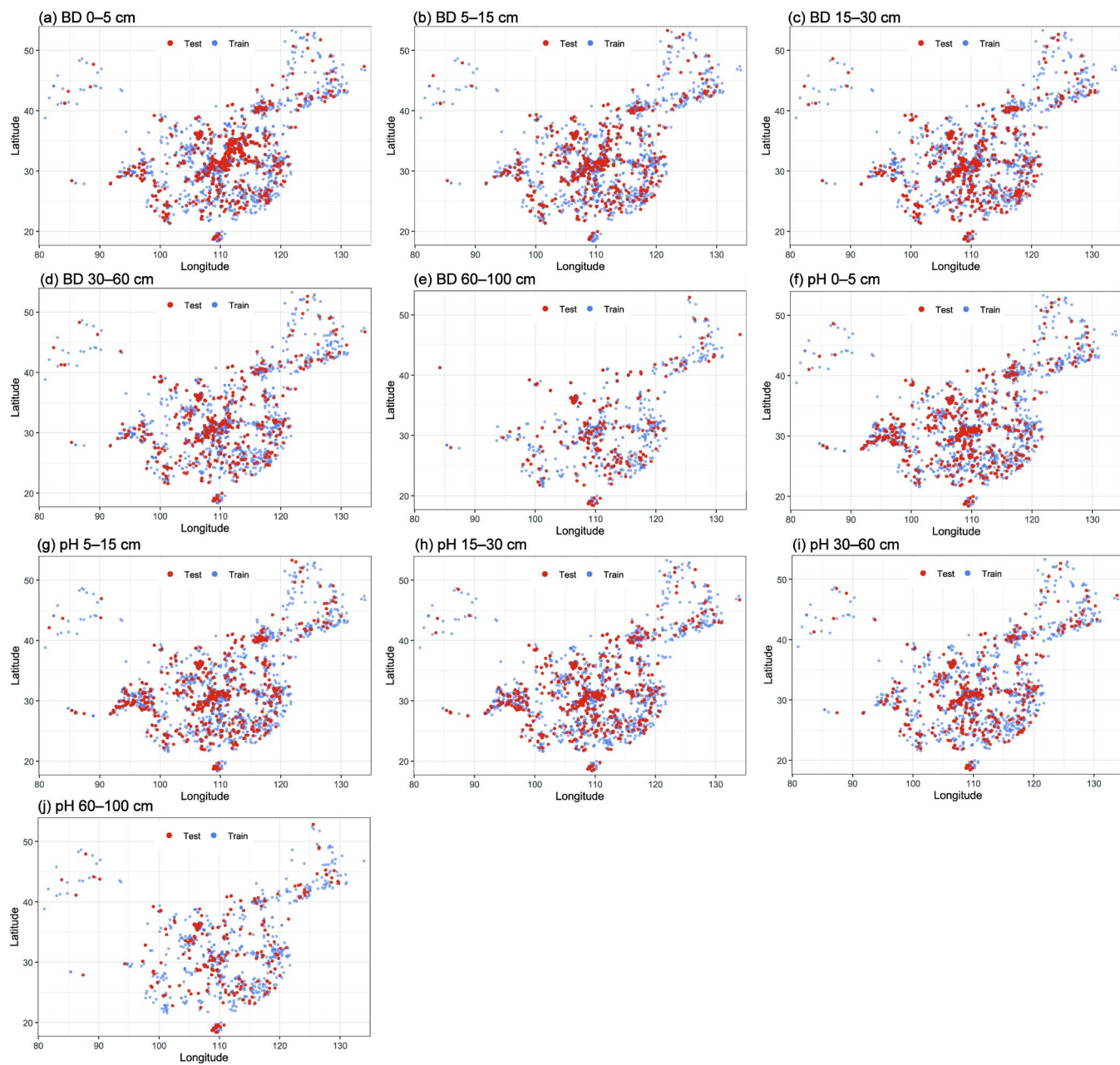


Figure S2. Spatial distributions of the training and validation datasets for bulk density (BD) and pH across different soil layers.

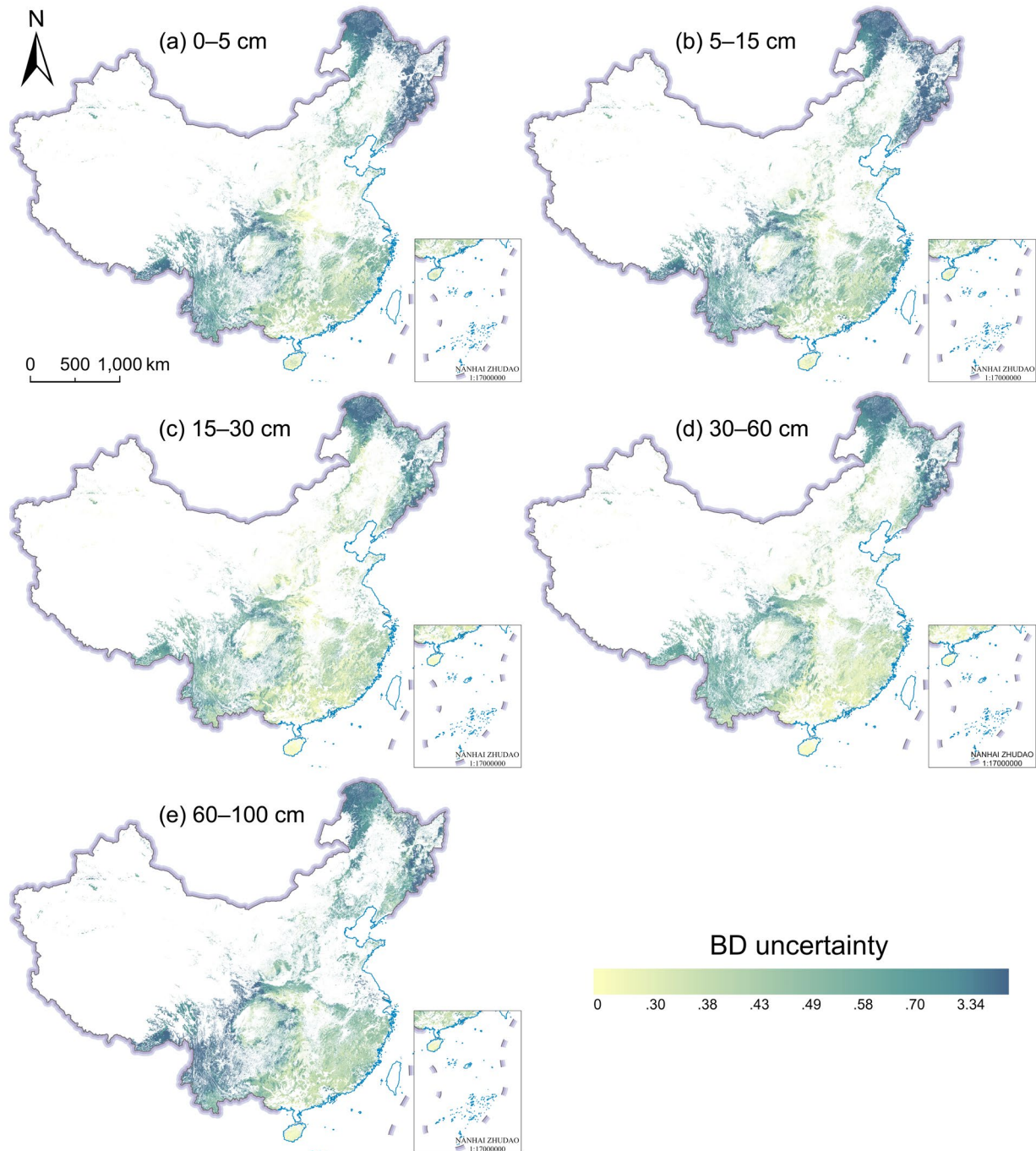


Figure S3. Uncertainty maps of predicted bulk density (BD) at 0–5 cm (a), 5–15 cm (b), 15–30 cm (c), 30–60 cm (d) and 60–100 cm (e) depths. Publisher's remark: please note that the above figure contains disputed territories.

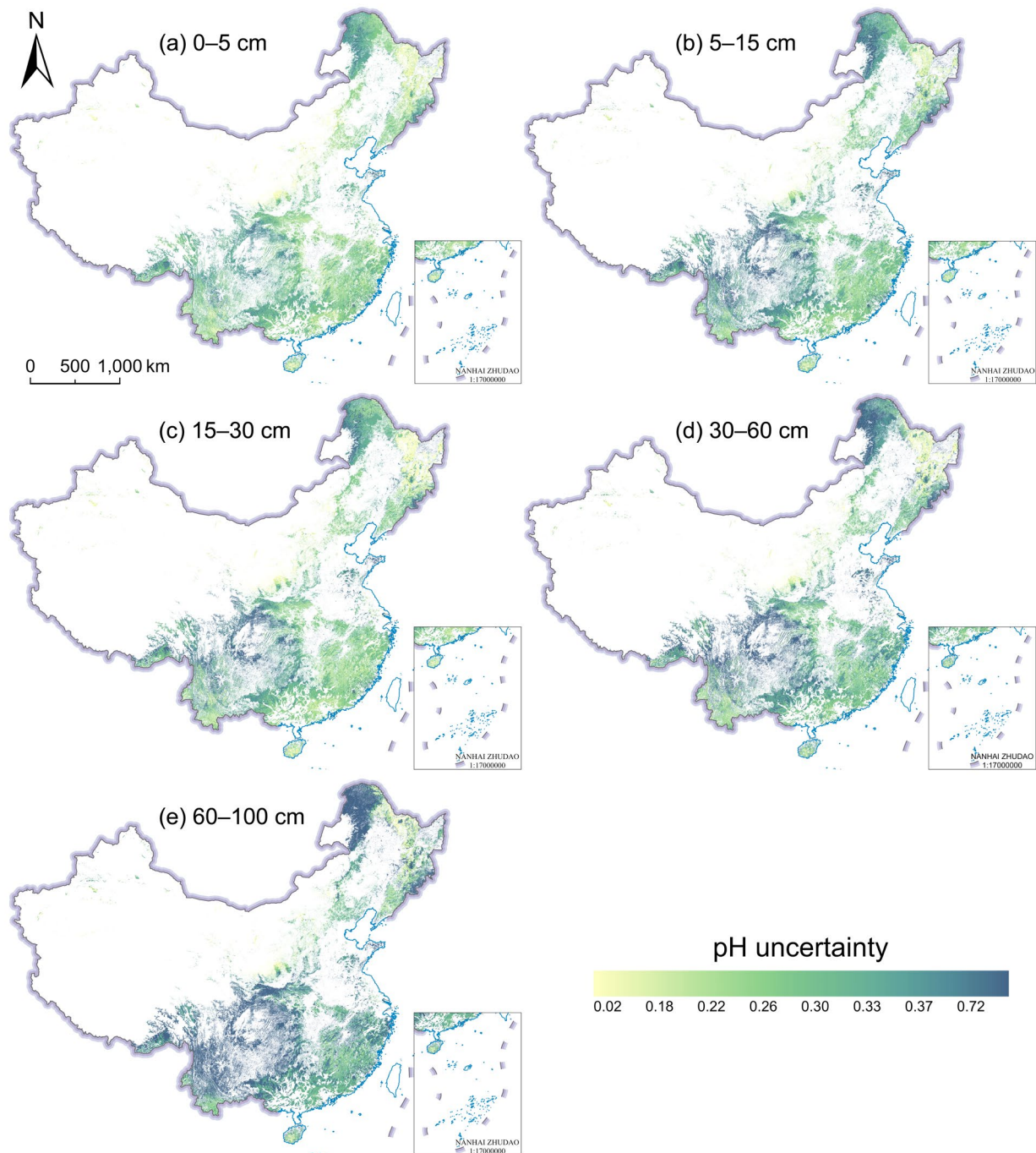
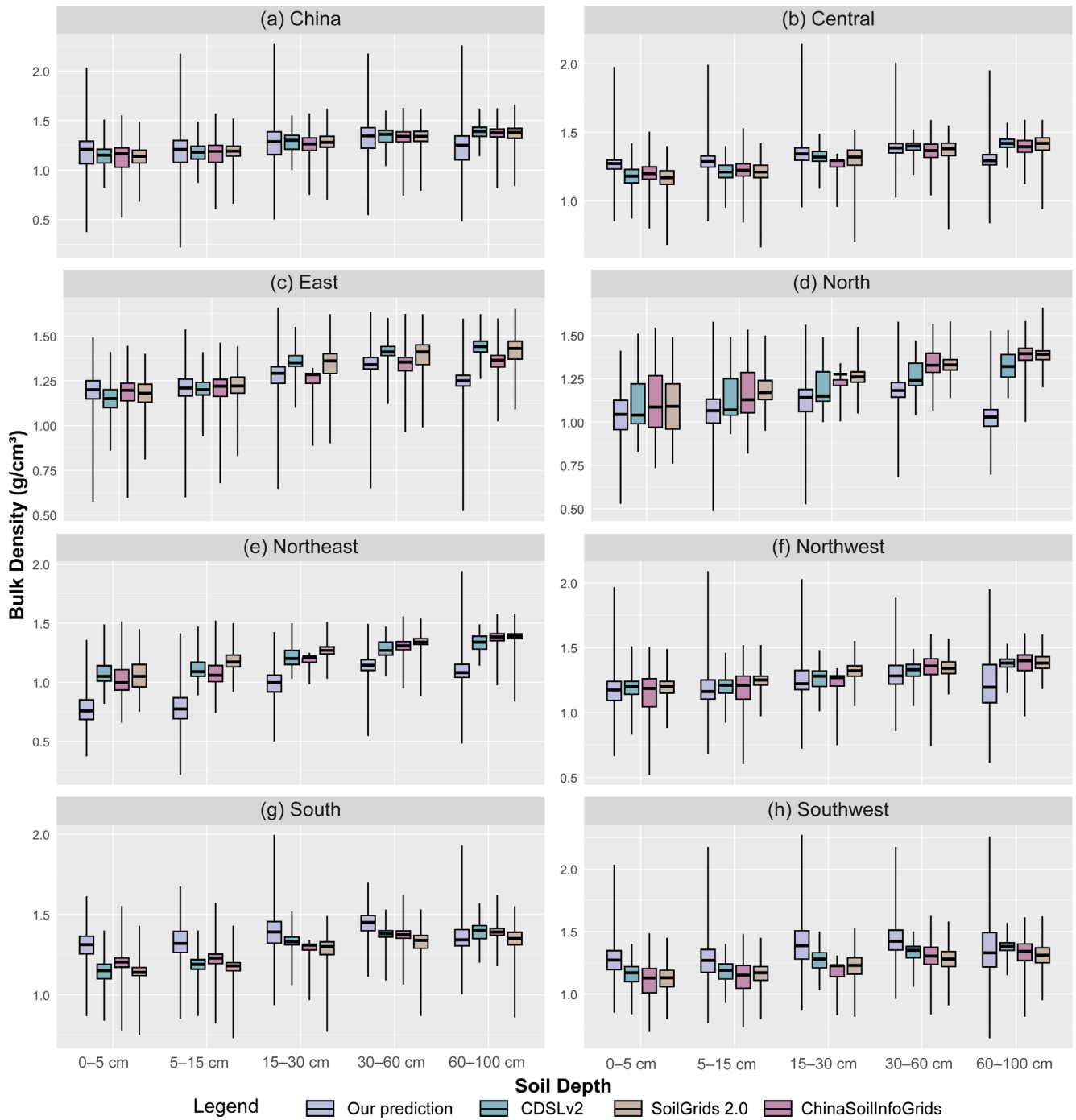
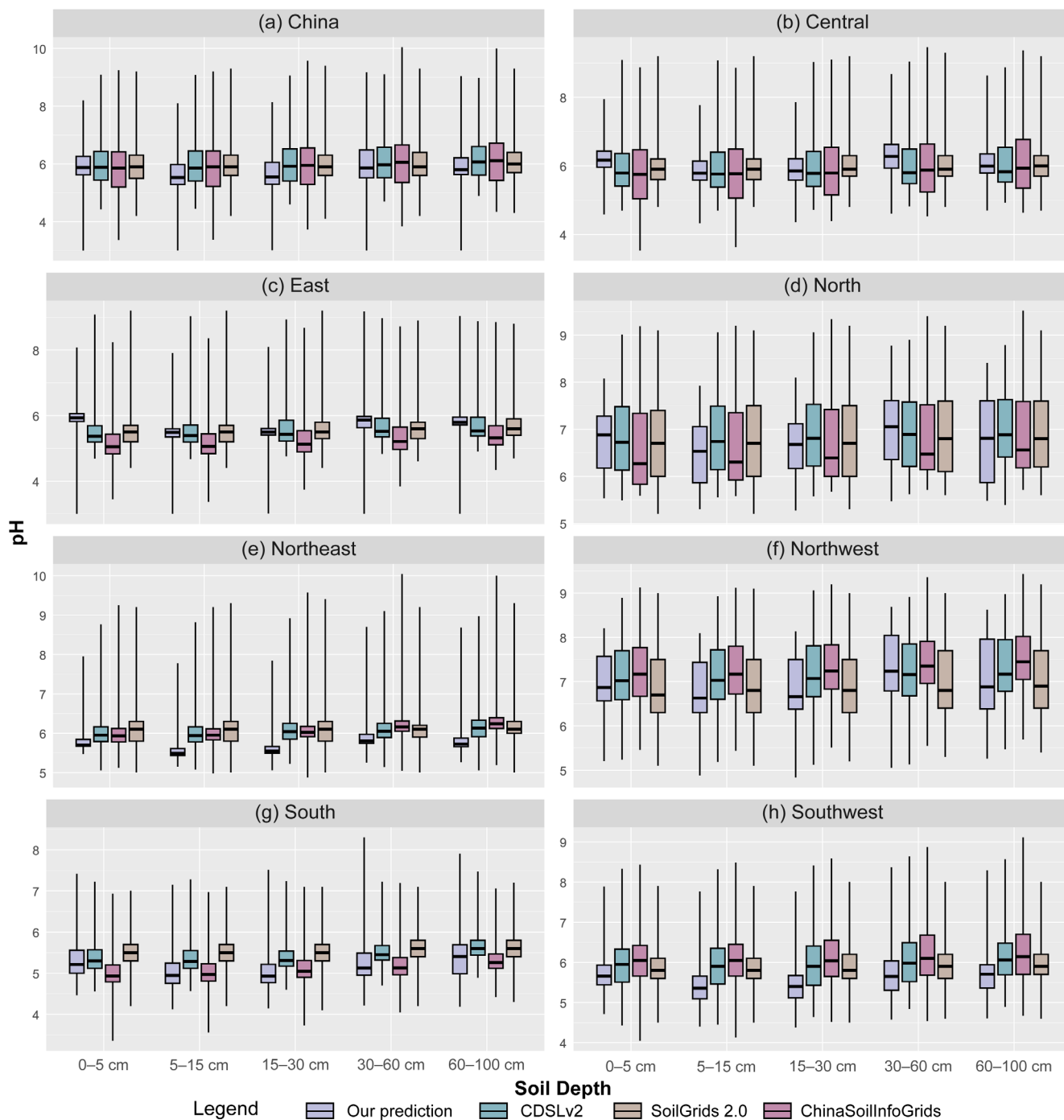


Figure S4. Uncertainty maps of predicted pH at 0–5 cm (a), 5–15 cm (b), 15–30 cm (c), 30–60 cm (d) and 60–100cm (e) depths.
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Figure S5. Statistical distribution of soil bulk density (BD) across five depths in (a) China and seven geographical regions: (b) Central, (c) East, (d) North, (e) Northeast, (f) Northwest, (g) South, (h) Southwest.



40 **Figure S6. Statistical distribution of soil pH across five depths in (a) China and seven geographical regions: (b) Central, (c) East, (d) North, (e) Northeast, (f) Northwest, (g) South, (h) Southwest.**

S2 Supplementary Tables

Table S1 Reference and comparison datasets for environmental covariates.

Name	Abbreviation	Scale/resolution	Category ^{a)}	Type ^{b)}	Source
Digital Elevation Model	Elevation	30 m	t	Q	(Peng et al., 2024)
Slope	Slope	30 m	t	Q	-
Aspect	Aspect	30 m	t	Q	-
Plan curvature	PlanCur	30 m	t	Q	-
Profile curvature	ProCur	30 m	t	Q	-
topographic wetness index	TWI	30 m	t	Q	-
Soil Surface Roughness	SSR	30 m	t	Q	-
Elevation Relief Ratio	ERR	30 m	t	Q	-
Local Position Index	LPI	30 m	t	Q	-
Geomorphological Types Map	Geomor	1:2.5 M	t	C	RESDC ^{c)}
Soil type	Soil	1:1 M	s	C	RESDC
Clay	Clay	1:1 M	s	Q	RESDC
Silt	Silt	1:1 M	s	Q	RESDC
Sand	Sand	1:1 M	s	Q	RESDC
Additive Log-Ratio of Sand to Clay	ALR1	1:1 M	s	Q	-
Additive Log-Ratio of Silt to Clay	ALR2	1:1 M	s	Q	-
Mean Annual Soil Moisture Content Index	SMCI_A	1 km	s	Q	(Yao et al., 2021)
Growing Season Soil Moisture Content Index	SMCI_GS	1 km	s	Q	(Yao et al., 2021)
Parent Material	PM	10 m	p	Q	COAH ^{d)}
Clay Mineral Ratio	CMR	10 m	p	Q	COAH
Geological map	Geol	1:2.5 M	p	C	(Pang et al., 2017)
Depth to Bedrock	DTB	100 m	p	Q	(Yan et al., 2020)
Forest type	FT	1:2.5 M	o	C	NESSDC ^{e)}
Mean Annual Normalized Difference Vegetation Index	NDVI_A	250 m	o	Q	MOD13Q1 ^{f)}

Growing Season Normalized Difference Vegetation Index	NDVI_GS	250 m	o	Q	MOD13Q1
Monthly Maximum Normalized Difference Vegetation Index	NDVI_MAX	250 m	o	Q	MOD13Q1
Mean Annual Leaf Area Index	LAI_A	500 m	o	Q	MOD15A2H ^{g)}
Growing Season Leaf Area Index	LAI_GS	500 m	o	Q	MOD15A2H
Net Primary Productivity	NPP	500 m	o	Q	MODIS17A3 ^{h)}
Mean Annual Temperature	TEM_A	1 km	c	Q	(Peng et al., 2019)
Mean Growing Season Temperature	TEM_GS	1 km	c	Q	(Peng et al., 2019)
Monthly Maximum Temperature	TEM_MAX	1 km	c	Q	(Peng et al., 2019)
Monthly Minimum Temperature	TEM_MIN	1 km	c	Q	(Peng et al., 2019)
Mean Annual Precipitation	PRE_A	1 km	c	Q	(Peng et al., 2019)
Growing Season Precipitation	PRE_GS	1 km	c	Q	(Peng et al., 2019)
Mean Annual Evapotranspiration	PET_A	1 km	c	Q	(Ding and Peng, 2021)
Growing Season Evapotranspiration	PET_GS	1 km	c	Q	(Ding and Peng, 2021)
Mean Annual Solar Radiation	SR_A	5 km	c	Q	(Abatzoglou et al., 2018)
Growing Season Solar Radiation	SR_GS	5 km	c	Q	(Abatzoglou et al., 2018)
Mean Annual Normalized Difference Water Index	NDWI_A	250 m	c	Q	MOD09A1 ⁱ⁾
Growing Season Normalized Difference Water Index	NDWI_GS	250 m	c	Q	MOD09A1

Note: a) t: topography; p: parent material; o: organisms; s: soil; c: climate. b) Q: quantitative; C: categorical. c) RESDC (Resources and
45 Environmental Sciences, <http://www.resdc.cn>). d) COAH (Copernicus Open Access Hub, <https://scihub.copernicus.eu>). e) NESSDC (National Earth System Science Data Center, <http://www.geodata.cn>). f) MOD13Q1 (<https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD13Q1>). g) MOD15A2H (<https://www.earthdata.nasa.gov/data/catalog/lpcloud-mod15a2h-061>). h) MODIS17A3 (<https://www.earthdata.nasa.gov/data/catalog/lpcloud-mod17a3hgf-061>). i) MOD09A1 (<https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD09A1>).

55 **Table S2. Source information for internal forest soil survey campaigns used in this study.**

Survey / project name	Year	Geographic coverage	Number of profiles
Typical Forest Soil Survey Project	2018–2020	Nationwide	1198
Henan Forest Soil Survey Project	2018-2020	Henan Province	800
Survey of Understory Vegetation and Soil in Tibet	2022	Tibet	19
Southwest China Transect and Forest Vegetation Survey	2019	Southwest China	36
Shennongjia Forest Soil Type Survey Project	2022	Shennongjia	68
Hubei Carbon Sink Survey Project	2019	Hubei Province	121
Economic Forest Survey in the Three Gorges Reservoir Area	2021	Three Gorges Reservoir Area	430
Masson Pine Plantation Survey	2018	Nationwide	147
Chongqing Carbon Sink Monitoring Project	2022	Chongqing	534
This study	2023	Nationwide	1003

Table S3. Number of sampling plots for bulk density (BD) (g/cm³) and pH in surface soil (0–5 cm) across different soil types in the training and independent validation datasets.

Soil Type	BD		pH		Soil Type	BD		pH	
	T ^{a)}	V ^{b)}	T	V		T	V	T	V
Brown coniferous forest soils	18	4	20	13	Fluvo-aquic soils	144	61	39	31
Torrid red soils	3	1	2	2	Bog soils	14	6	19	15
Cinnamon soils	317	79	134	90	Peaty bog soils	1	1	2	1
Gray-cinnamon soils	301	70	165	105	Meadow solonchaks	3	1	2	2
Black soils	5	1	2	2	Coastal solonchaks	4	1	2	2
Gray-forest soils	2	0	2	2	Paddy soils	143	58	121	91
Chernozems	6	1	4	3	Irrigated warped soils	3	1	2	2
Castanozems	30	7	18	12	Irrigated desert soils	3	1	2	2
Castano-cinnamon soils	4	1	7	5	Felty soils	20	9	57	45
Dark loessial soils	18	4	10	7	Dark felty soils	84	35	107	81
Sierozems	7	2	5	3	Cold calcic soils	3	1	39	30
Yellow soils	113	27	80	51	Cold brown calcic soils	1	1	56	42
Neo-alluvial soils	51	13	13	8	Frigid frozen soils	4	1	3	2
Aeolian soils	62	14	10	7	Latosols	21	9	12	9
Limestone soils	138	34	92	61	Latosolic red soils	105	45	63	50
Volcanic soils	4	1	3	2	Red soils	282	115	211	159
Purplish soils	126	31	121	80	Yellow soils	223	96	264	208
Lithosols	22	5	4	2	Yellow-brown soils	330	135	181	137
Skeletal soils	139	35	55	37	Yellow-cinnamon soils	118	50	20	15
Meadow soils	41	10	42	27	Brown soils	224	92	145	109
Sajiang black soils	6	2	2	1	Dark-brown soils	87	37	90	71
Mountain meadow soils	13	3	4	2	Bleached baijiang soils	6	2	5	4
Meadow soils	2	1	4	2					

60 Note: a) T: Training datasets. b) V: Validation datasets.

Table S4. Number of sampling plots for bulk density (BD) and pH in surface soil (0–5 cm) across different geomorphological types in the training and independent validation datasets.

Geomor Types	BD		pH		Geomor Types	BD		pH	
	T ^{a)}	V ^{b)}	T	V		T	V	T	V
Mountain	2897	636	2589	688	Platform	78	48	64	39
Loess ridge-hill	44	10	42	12	Plain	251	97	332	129
Loess terrace-tableland	11	2	5	1	Alluvial fan plain	141	87	6	4
Loess tableland	34	8	28	7	Low floodplain	5	2	6	2
Gully erosion landform	3	1	3	1					

Note: a) T: Training datasets. b) V: Validation datasets.

65 **Table S5. Number of sampling plots for bulk density (BD) and pH in surface soil (0–5 cm) across different forest types in the training and independent validation datasets.**

Forest Type	BD		pH	
	T ^{a)}	V ^{b)}	T	V
Coniferous forest	1837	459	1868	467
Broad-leaved forest	1390	595	1085	465
Mixed coniferous-broadleaf forest	56	18	55	18

Note: a) T: Training datasets. b) V: Validation datasets.

Table S6. Statistical summary of soil bulk density (BD) (g/cm³) and pH across five depth intervals.

Property	Depth (cm)	N	Mean	SD	Min	Max	Skewness
BD	0–5	4356	1.206	0.261	0.152	2.057	0.162
	5–15	3522	1.209	0.288	0.184	2.291	0.317
	15–30	3488	1.287	0.269	0.201	2.271	0.422
	30–60	2973	1.340	0.269	0.207	2.215	0.393
	60–100	1506	1.242	0.308	0.257	2.291	0.367
pH	0–5	3963	6.066	0.909	4.000	8.440	0.045
	5–15	3962	6.131	0.991	4.000	8.515	0.111
	15–30	3816	6.172	1.005	4.030	8.420	0.087
	30–60	2783	6.458	1.198	4.040	8.640	0.194
	60–100	1454	6.466	1.327	4.040	8.704	0.119

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Table S7 Tuned model parameters for soil bulk density (BD) and pH considered at five depth intervals.

Property	Depth (cm)	mtry	node.size	num.trees
BD	0–5	4	9	1163
	5–15	3	4	1421
	15–30	2	4	788
	30–60	2	4	1179
	60–100	9	3	947
pH	0–5	7	9	941
	5–15	5	11	607
	15–30	13	6	828
	30–60	9	9	252
	60–100	3	5	509

Table S8 Summary statistics of the soil bulk density (BD) (g/cm³) and pH.

Property	Depth (cm)	Minimum	25%	Mean	Median	75%	Maximum	STD
BD	0–5	0.372	1.062	1.157	1.208	1.291	2.034	0.213
	5–15	0.217	1.078	1.165	1.208	1.299	2.175	0.218
	15–30	0.499	1.155	1.267	1.288	1.386	2.272	0.189
	30–60	0.545	1.221	1.336	1.344	1.427	2.176	0.152
	60–100	0.479	1.104	1.251	1.250	1.343	2.258	0.199
pH	0–5	3.000	5.618	5.997	5.874	6.260	8.204	0.654
	5–15	3.002	5.285	5.697	5.528	5.981	8.097	0.685
	15–30	3.012	5.297	5.731	5.545	6.055	8.136	0.710
	30–60	3.000	5.518	6.056	5.862	6.482	9.179	0.814
	60–100	3.004	5.634	6.013	5.800	6.210	9.036	0.755

Table S9 FRFS–Selected environmental covariates for soil bulk density (BD) at five depth intervals.

Depth (cm)	Abbreviation	VIF	N	Depth (cm)	Abbreviation	VIF	N
0–5	ALR2	1.551	13	15–30	Elevation	2.516	7
	DTB	1.765			PRE_A	2.520	
	SR_GS	1.795			PET_A	2.805	
	Geomor	1.825		Soil	2.644		
	NDVI_GS	2.092		30–60	DTB	1.173	9
	NDVI_MAX	2.266			LAI_GS	1.190	
	NPP	2.714			SR_GS	1.335	
	NDWI_A	3.795			NPP	2.284	
	Elevation	4.798			Elevation	2.601	
	PRE_A	5.116			NDWI_A	3.262	
	PET_GS	9.296			PET_A	3.355	
	PET_A	9.741			PRE_A	3.620	
	Soil	3.335			Soil	2.604	
5–15	DTB	1.192	7	60–100	DTB	1.161	9
	SR_GS	1.431			SR_GS	1.212	
	NDWI_GS	1.444			LAI_GS	1.265	
	PRE_A	2.357			NPP	2.708	
	Elevation	2.550			Elevation	2.935	
	PET_A	2.851			PET_A	4.299	
15–30	Soil	2.664	7	NDWI_A	4.466		
	LAI_A	1.217		PRE_A	4.773		
	SR_GS	1.432		Soil	2.447		
	NPP	1.801					

85 Table S10 FRFS–Selected environmental covariates for soil pH at five depth intervals.

Depth (cm)	Abbreviation	VIF	N	Depth (cm)	Abbreviation	VIF	N
0–5	FT	1.117	13	15–30	PRE_A	4.009	12
	LAI_A	1.228			NDWI_A	5.454	
	DTB	1.246			Soil	2.678	
	SR_GS	1.479		30–60	FT	1.182	16
	NDVI_MAX	2.748			LAI_A	1.300	
	NPP	2.801			Silt	1.333	
	CMR	2.856			DTB	1.388	
	PET_A	3.033			Geomor	1.433	
	PM	3.045			SR_GS	1.488	
	Elevation	3.291			NDVI_MAX	2.101	
	PRE_A	3.995			PM	2.129	
	NDWI_A	6.519			ALR2	2.203	
	Soil	2.115			NPP	2.552	
5–15	Silt	1.102	12	NDVI_A	2.593		
	LAI_A	1.231		Elevation	2.672		
	DTB	1.238		PRE_A	3.928		
	SR_GS	1.405		PET_A	4.112		
	PM	2.514		NDWI_A	4.729		
	NDVI_MAX	2.700		Soil	2.547		
	NPP	2.785		60–100	SR_GS	1.471	15
	PET_A	3.012			LAI_A	1.558	
	Elevation	3.144			DTB	1.566	
	PRE_A	3.976			Geomor	1.769	
	NDWI_A	5.610			ALR2	2.037	
Soil	2.548	NDVI_GS	2.162				
15–30	Silt	1.102	12	PM	2.451		
	DTB	1.390		NPP	3.022		
	SR_GS	1.394		Elevation	3.184		
	Geomor	1.413		NDVI_MAX	3.450		
	PM	2.497		PET_A	4.850		
	NDVI_MAX	2.671		PRE_A	5.497		
	NPP	2.886		NDWI_GS	6.082		
	PET_A	3.053		NDWI_A	7.105		
	Elevation	3.111		Soil	2.024		

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