A 3D mixed model for soil organic carbon mapping in mountainous subtropics

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Why use 3D soil mapping?

There is a need to asses changing soil organic carbon (SOC) concentrations and stocks as indicators for potential soil fertility loss at landscape level. With 3D modelling, SOC distribution across soil depth and in space can be predicted in one single model. Many areas in the mountainous subtropics are difficult to access which requires optimized sampling schemes and prediction models. As an option with high potential for such areas, we tested a mixed model as a 3D digital soil mapping tool that can handle unbalanced datasets and upscaling.

Study area and design

- Study area: 43 km²; upscaling area (Naban reserve): 270 km²
- Sampling stratification: cost constrained conditioned Latin hypercube sampling (CC-CLHS) based on digital covariates: *elevation, slope, aspect, land use map*
- Soil sampling at 120 points, including 11 profiles
- Measurements: *organic C content (TOC) of all pedogenetic horizons, bulk density (BD) of topsoil and all horizons in profiles*
- Calculated: *soil organic carbon density (SOCD) = TOC x BD*

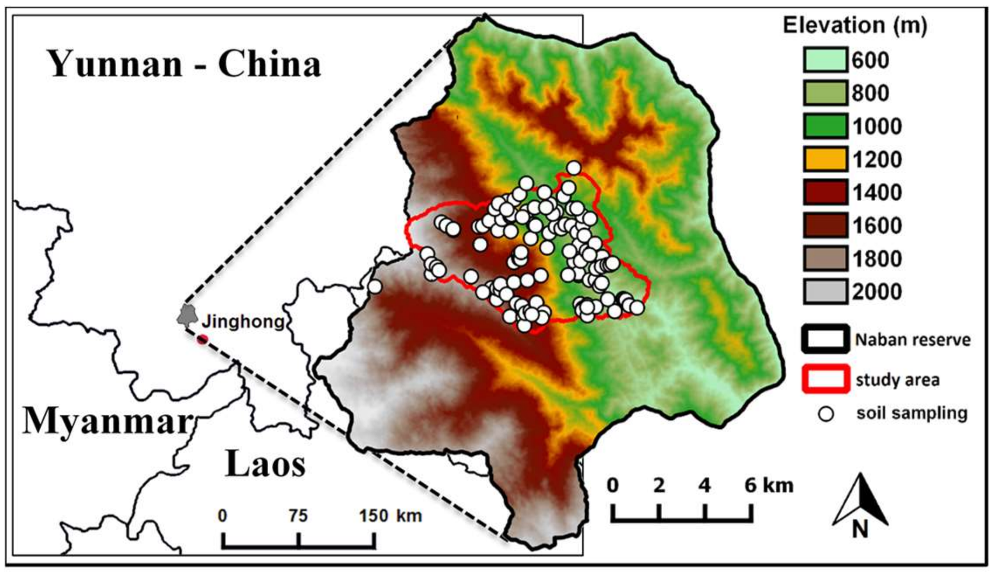

Fig. 1: Location of the Naban Reserve and the study area, digital elevation map and soil sampling points

New 3D mixed model approach

The 3D mixed model over continuous depth (MMCD) approach uses digital covariates as fixed effects and accounts for correlation of different horizons from the same profile by random effects:

$$y_{il} = ß_0 + ß_1 d_i + ß_2 {d_i}^2 + \sum_{j=1}^{k} (ß_{j.1} f_j + ß_{j.2} f_j d_i + ß_{j.3} f_j {d_i}^2) + u_{l1} + u_{l2} d_i + u_{l3} {d_i}^2 + \varepsilon_{il}$$

(y_{il} = measured value at the i-th depth of the l-th point, d = mean depth of horizon, f = fixed effects, ß = fixed effects coefficients, u = random effects coefficients, ε_{il} = residual error term)

The MMCD approach can be applied to unbalanced datasets (e.g. SOCD) and produce maps with 95% prediction intervals:

$$\bar{y} \pm 1.96\sqrt{s_f^2 + s_r^2 + \varepsilon^2}$$

($\bar{y}$ is the model-predicted value and s_f^2, s_r^2 and ε^2 are the variance components of the fixed and random effects and the remaining residual, respectively)

Evaluation of model performance by modelling efficiency (EF):

$$EF = \frac{(\sum_{i=1}^{n} (O_i - \bar{O})^2 - \sum_{i=1}^{n} (O_i - P_i)^2)}{\sum_{i=1}^{n} (O_i - \bar{O})^2}$$

(O_i = measured value, $\bar{O}$ = mean of measured values, and P_i = predicted value)
EF = 1 means a perfect simulation; EF < 0 means the prediction is worse than taking the mean

Results and performance of MMCD

Table 1: Evaluation statistics of different TOC prediction models for standard horizons and original horizon structure. Root mean square error (RMSE) and modelling efficiency (EF) were computed by leaving a third out cross validation (1000 iterations)

model	lower horizon boarder (cm)	RMSE of the mean	modelling efficiency (EF)
3D mixed model over continuous depth (MMCD)	5	25%	0.7
	15	22%	0.77
	30	25%	0.73
	60	37%	0.48
	100	49%	0.17
	original horizons	35%	0.72
Kriging with external drift for 2D depth layers	5	22%	0.78
	15	22%	0.78
	30	25%	0.71
	60	38%	0.44
	100	49%	0.16
3D Kriging with external drift (3)	5	24%	0.71
	15	22%	0.76
	30	24%	0.72
	60	36%	0.49
	100	50%	0.12
	original horizons	35%	0.73

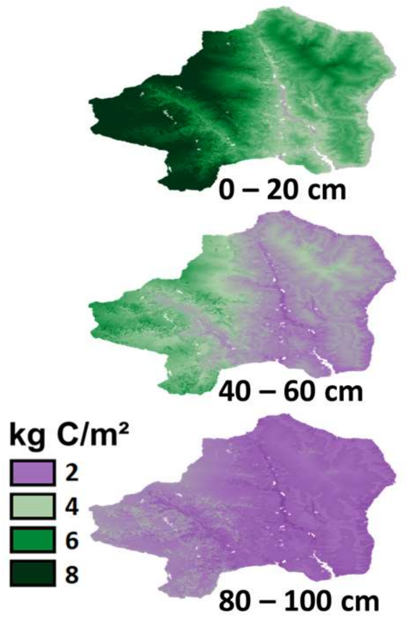

Fig. 2: MMCD predictions of SOCD for different depth layers. The size of depth intervals can be chosen by the modeler

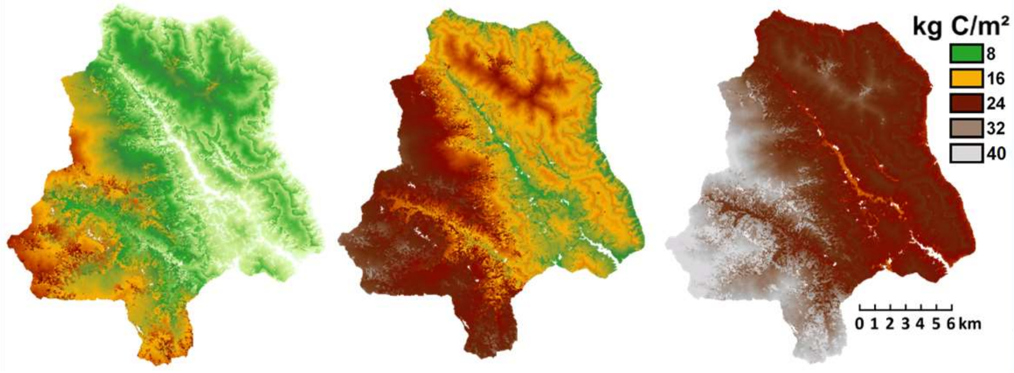

Fig. 3: Predicted SOCD in the Naban Reserve down to 1 m depth based on a MMCD (middle), with lower (left) and upper (right) 95 percent prediction intervals.

Table 2: Evaluation statistics of SOCD prediction using cross validation and three datasets from outside the study area for evaluation of upscaling. Root mean square error (RMSE), mean error (ME) and modelling efficiency (EF)

evaluation dataset	RMSE (kg C/m³)	RMSE of the mean	ME (kg C/m³)	modelling efficiency (EF)	Percent in 95% prediction limits
full dataset - cross validation	4.99	21%	-0.27	0.75	n.d.
profiles only - cross validation	4.98	30%	-0.29	0.75	n.d.
full profile SOC density	3.53	31%	2.51	0.63	0.99
Wolff and Zhang (2010)	7.09	45%	4.44	0.39	0.79
Walkley Black topsoil	5.87	26%	0.66	-0.08	0.94

Conclusions

The MMCD approach

- Is effective for 3D soil mapping any chosen depth interval
- Can be used for unbalanced datasets with less subsoil data
- Is simple to apply and as effective as geostatistic models, but has the advantage, that it can be upscaled, if well calibrated
- The combination of CC-CLHS with MMCD is very suitable for mountainous difficult access landscapes

Literature

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Acknowledgements:. This study was part of the Sino-German research project "Sustainable Rubber Cultivation in the Mekong Region" (SURUMER), funded by the German Federal Ministry of Education and Research (BMBF, Support Code: (FKZ): 01 LL 0919).

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Publication: M. Laub, S. Blagodatsky, R. Lang, X. Yang, and G. Cadisch, "A mixed model for landscape soil organic carbon prediction across continuous profile depth in the mountainous subtropics," Geoderma, vol. 330, no. November 2018, pp. 177–192, Nov. 2018.