



Soil mapping goes digital - the GlobalSoilMap experience

Alex. McBratney

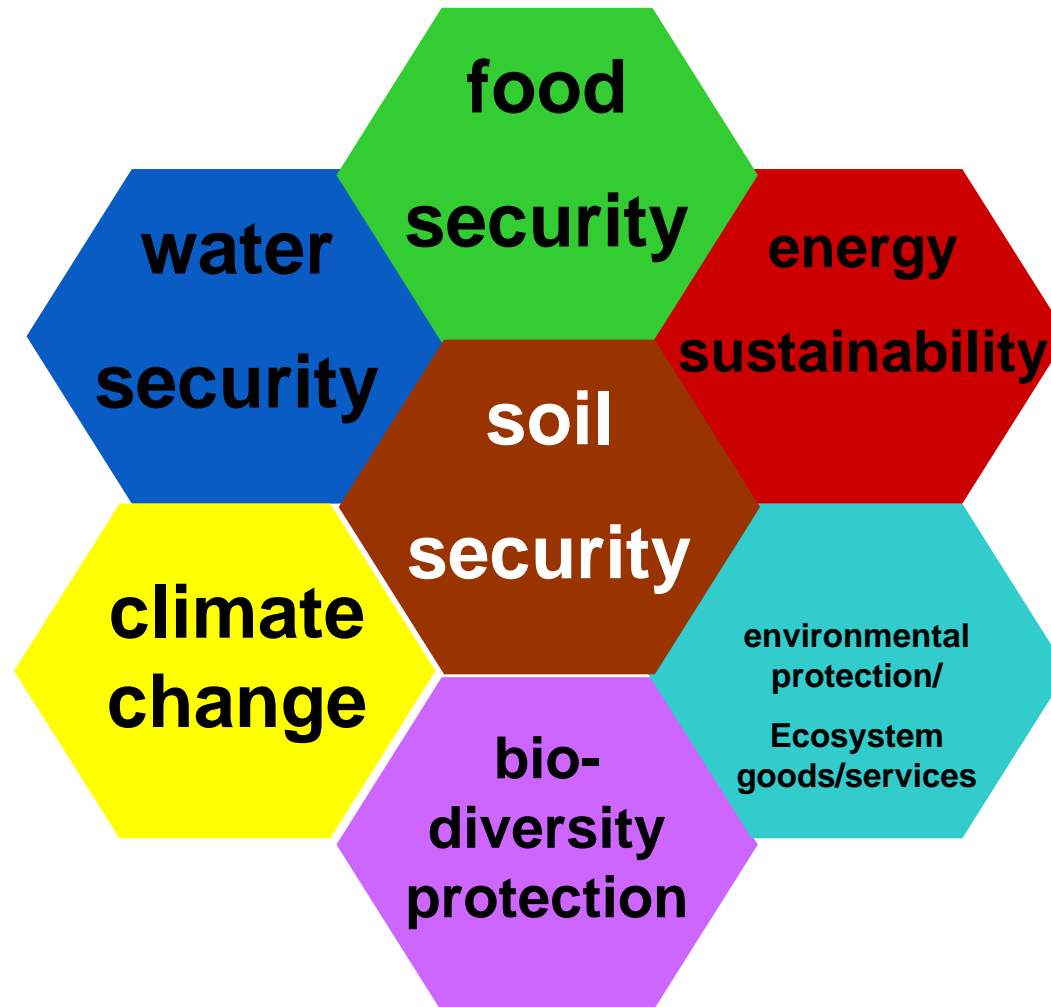
Faculty of Agriculture, Food & Natural Resources
The University of Sydney

International Union of Soil Sciences

Why are we here?

Soil Security

the maintenance or improvement of the world's soil resource so it can:-
provide sufficient food feed and fibre and fresh water, contribute to energy sustainability and climate stability, maintain biodiversity and overall environmental protection and ecosystem goods & services.



People need
quantitative
information and our
expertise for that

Analogue -> Digital

1939 Marconi - Model 709
9" screen (UK)



© 2002 TVhistory.TV (TMK)

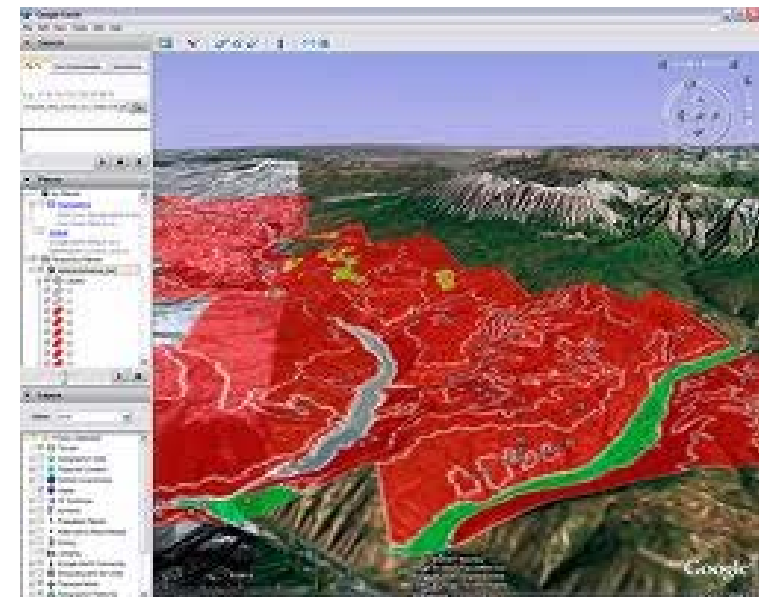
Television



Television

	Analogue	Digital
System	Scanning lines	Pixelated
Resolution	? 625 lines	1920 x 1080
Metadata	none	EPG
Interaction	On/off	Freeze, delay, playback
Speed	Instantaneous	Delay

Soil Maps



Soil Maps

	Analogue	Digital
System	Choropleth classes /legend	SSIS - Vector & pixels- classes and properties & pixel
Resolution	scale	pixels/unit length
Metadata	separate	attached
Interaction	Indirect	Direct and detailed
Speed	Instantaneous	Delay

Digital Soil Mapping (DSM)



“the creation and population of spatial soil information systems by numerical models inferring the spatial and temporal variations of soil types and soil properties from soil observation and knowledge and from related environmental variables”

(Lagacherie and McBratney 2007).

Spatial data on soil-forming factors

$$S = f (S, C, O, R, P, A, N) + \epsilon$$



Soil class or soil property



Climate



Climate model outputs



Organisms



Remote sensing of vegetation and land use



Relief



DEMs and their derivatives



Parent Material



Digitized geological maps



Age



Expert knowledge ?

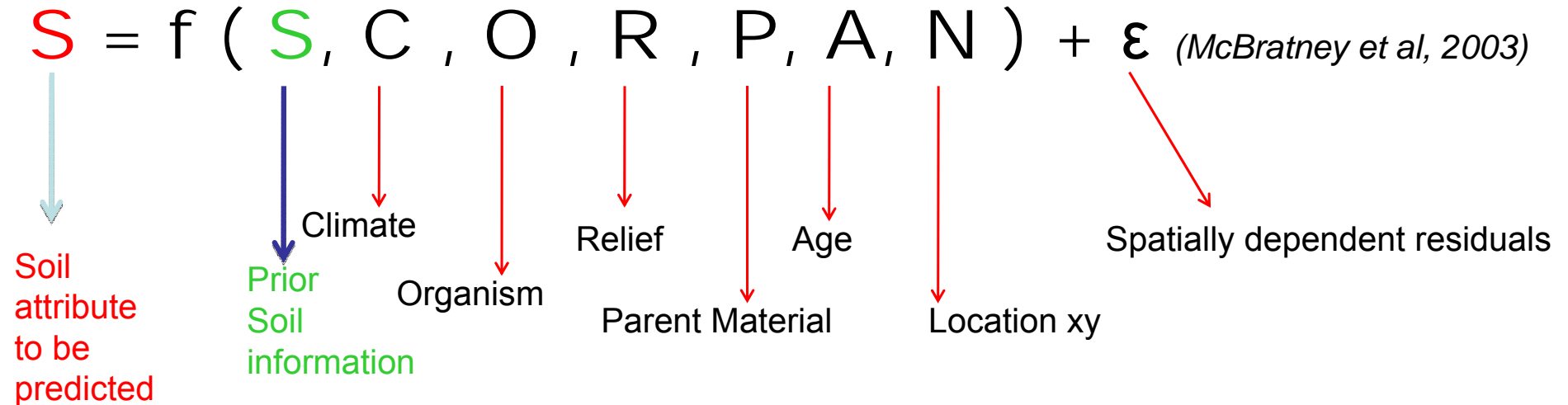


Location xy



Maps of distance from landscape features

Prior soil information



Legacy soil data (soil profiles, soil maps, expert knowledge)

Soil sensing (remote & proximal)

Recognising & Collecting legacy soil data



- **Rescuing/Saving soil data (scanning – descriptions, maps, notes)**
- **Defining and populating a soil data model**
- **Filtering data**
 - Digitising errors
 - Geo-referencing errors
- **Harmonising soil data**
 - Harmonisation of soil descriptions (e.g. textural classes,)
 - Harmonisation of soil depths (Malone et al, 2009)
 - **Defining modality of use - respecting data-owner rights**

Spatial inference models

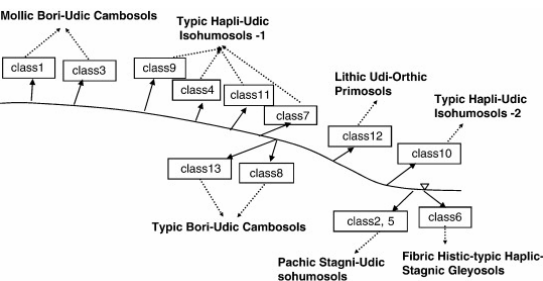
Interpolation/extrapolation function calibrated (validated) over limited sets of soil observations (profile, maps, ...).

Quantitative soil surveyor approaches

(largely knowledge driven)

- Human and artificial intelligence model e.g. SoLIM (Zhu et al. 2009)

$$s(x,y) = f(s,r)$$

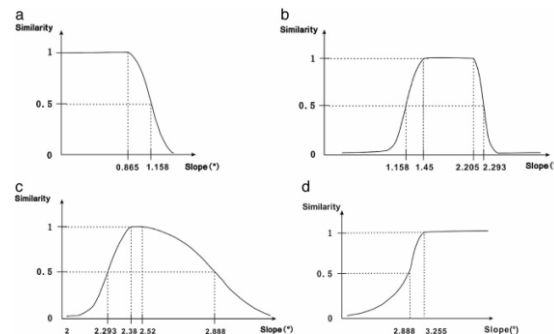


Pedometric approaches (largely data-driven)

Non-linear environmental correlation models

$$s(x,y) = f(\{c,o,r,p,a,n\}(x,y))$$

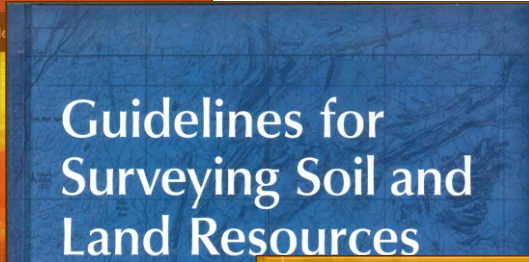
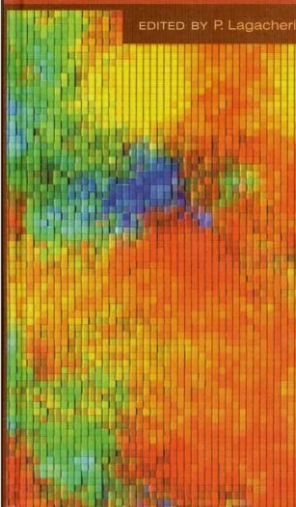
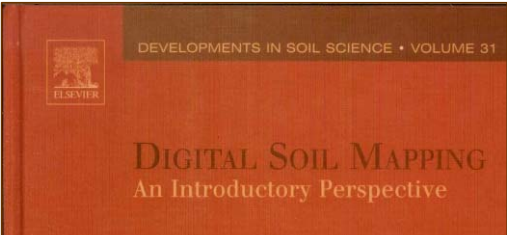
- Regression, classification trees, neural networks, random forests etc.



Pedo-Geostatistical models

$$s(x,y) = f(s(x+u, y+v), \{c,o,r,p,a,n\}(x,y))$$

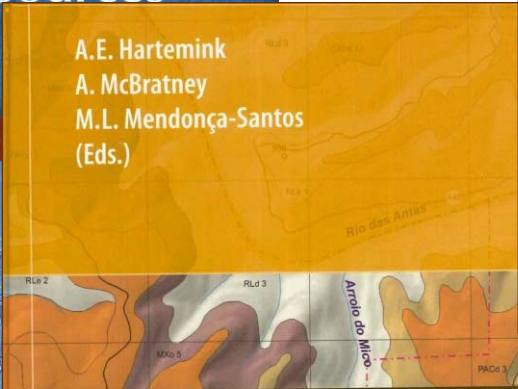
- Co-kriging, regression kriging, conditional simulation etc.



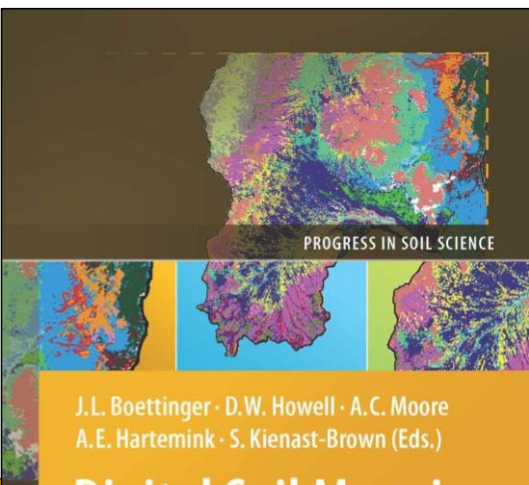
Guidelines for Surveying Soil and Land Resources

SECOND EDITION

NJ McKenzie, MJ Grundy,



A.E. Hartemink
A. McBratney
M.L. Mendonça-Santos
(Eds.)



J.L. Boettinger · D.W. Howell · A.C. Moore
A.E. Hartemink · S. Kienast-Brown (Eds.)

Digital Soil Mapping

Bridging Research,
Environmental Applications
and Operation

POLICYFORUM

Digital Soil Map of the World

Pedro A. Sanchez,^{1*} Sonya Ahmed,² Florence Carré,³ Alfred E. Hartemink,⁴ Jonathan Hempel,⁴ Jerome Huising,⁵ Philippe Lagacherie,⁶ Alex B. McBratney,⁷ Neil J. McKenzie,⁸ Maria de Lourdes Mendonça-Santos,⁹ Budiman Minasny,¹⁰ Luca Montanarella,¹¹ Peter Odeh,¹² Cheryl A. Palm,¹³ Jeffrey D. Sachs,¹⁴ Keith D. Shepherd,¹⁵ Tor-Gunnar Vagen,¹⁶ Bernard Vanlauwe,¹⁷ Markus G. Walsh,¹⁸ Leigh A. Winowiecki,¹⁹ Gan-Lin Zhang²⁰

Soils are increasingly recognized as major contributors to ecosystem services such as food production and climate regulation (1, 2), and demand for up-to-date and relevant soil information is soaring. But communicating such information among diverse audiences remains challenging because of inconsistent use of technical jargon, and outdated, imprecise methods. Also, spatial resolutions of soil maps for most parts of the world are too low to help with practical land management. While other earth sciences (e.g., climatology, geology) have become more quantitative and have taken advantage of the digital revolution, conventional soil mapping delineates space mostly according to qualitative criteria and renders maps using a series of polygons, which limits resolution. These maps do not adequately express the complexity of soils across a landscape in an easily understandable way.

The Food and Agriculture Organization (FAO) of the United Nations (UN) and the UN Educational, Scientific and Cultural Organization (UNESCO) published the first world soil map in 1961, using a single soil classification terminology (3). The map has been utilized in many global studies on climate change, food production, and land degradation. But its low resolution (1:5 million scale) is not suitable for land management decisions at field or catchment scales. One of the most-cited soil degradation studies, the *Global Assessment of Human Induced Soil Degradation*, is based on expert judgment by a few individuals, has very low resolution (1:50 million scale), and lacks quantitative information on soil properties that indicate

the degree of soil degradation (4). At present, 109 countries have conventional soil maps at a scale of 1:1 million or finer, but they cover only 31% of the Earth's ice-free land surface, leaving the remaining countries reliant on the FAO-UNESCO map (5). [See supporting online material (SOM) for more history.]

To address these many shortcomings, soil scientists should produce a fine-resolution, three-dimensional grid of the functional properties of soils relevant to users. We call for development of a freely accessible, Web-based digital soil map of the world that will

make georeferenced soil information readily available for land-users, scientists, and policy-makers. A foundation for such an effort is being laid by the GlobalSoilMap.net (GSM) project. This effort originated in 2006 (6) in response to policy-makers' frustrations at being unable to get quantitative answers to questions such as: How much carbon is sequestered or emitted by soils in a particular region? What is its impact on biomass production and human health? How do such estimates change over time?

The GSM consortium's overall approach consists of three main components: digital soil mapping, soil management recommen-



Digital soil mapping began in the 1970s (6) and accelerated significantly in the 1990s because of advances in information and remote-sensing technologies, computing, statistics and modeling, spatial information and global positioning systems, measurement systems (such as infrared spectroscopy), and in

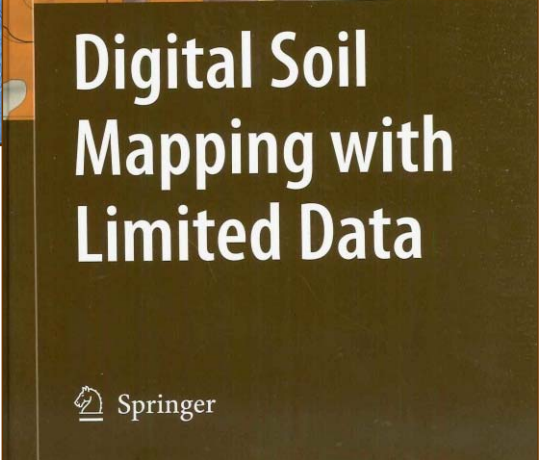
datums, and serving the end users—all of them backed by a robust cyberinfrastructure. [See fig. S1, expanded from (7).] Specific countries may add their own modifications.

Maps can provide soil inputs (e.g., texture, organic carbon, and soil-depth parameters) to models predicting land-cover changes in response to global climatic and human disturbances.

2006

2010

2007



Digital Soil Mapping with Limited Data

Springer

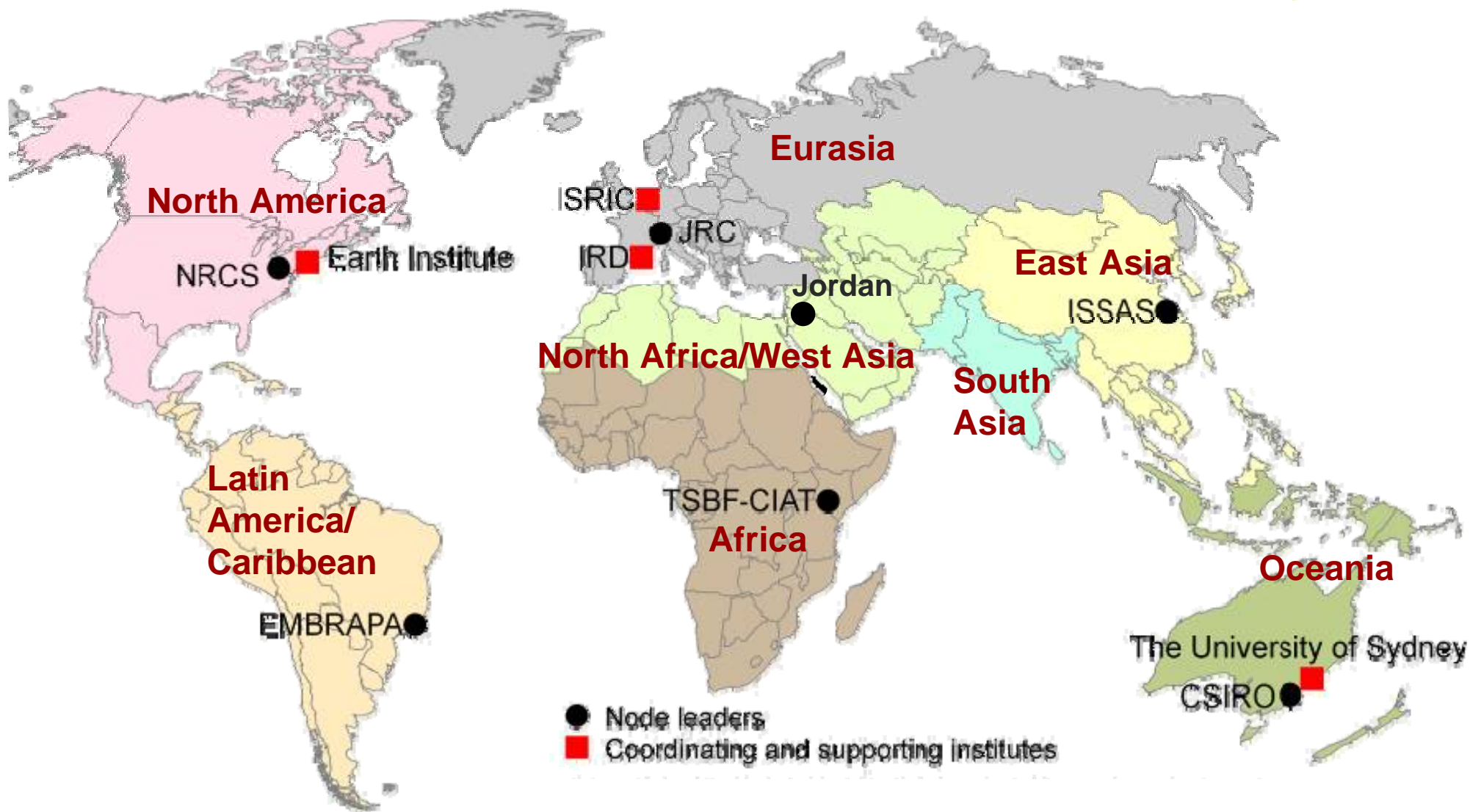
2008

¹Earth Institute at Columbia University, 61 Route 9W, Palisades, NY 10964, USA. ²Soil Research Centre, European Commission, 25010 Itera, UK. ³Soil World Soil Information, 6705 K, Wageningen, Netherlands. ⁴National Soil Survey Center, U.S. Department of Agriculture Natural Resources Conservation Service, Lincoln, NE 68506, USA. ⁵National Soil Biology and Fertility Institute of the International Center for Tropical Agriculture, Post Office Box 50077, Nairobi, Kenya. ⁶laboratoire d'Étude des Interactions Sol-Agrosystème-atmosphère, Institut National pour la Recherche Agronomique, Institut de Recherche pour le Développement, Soudra, 14000 Montpellier 1, France. ⁷School of Agriculture, Food and Natural Resources, The University of Sydney, NSW 2006, Australia. ⁸Commonwealth Scientific and Industrial Research Organization (CSIRO) Land and Water, Government Post Office Box 1666, Canberra, ACT, 2601, Australia. ⁹18800/Brasilia Agricultural Research for Sustainable, The National Center of Soil Research, Rua Jardim Buarque, 1624, 22.460-000, Rio de Janeiro, Brazil. ¹⁰World Agroforestry Centre, Post Office Box 10677-00100, Nairobi 00100, Kenya. ¹¹World Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science of the Chinese Academy of Sciences, Nanjing, China.

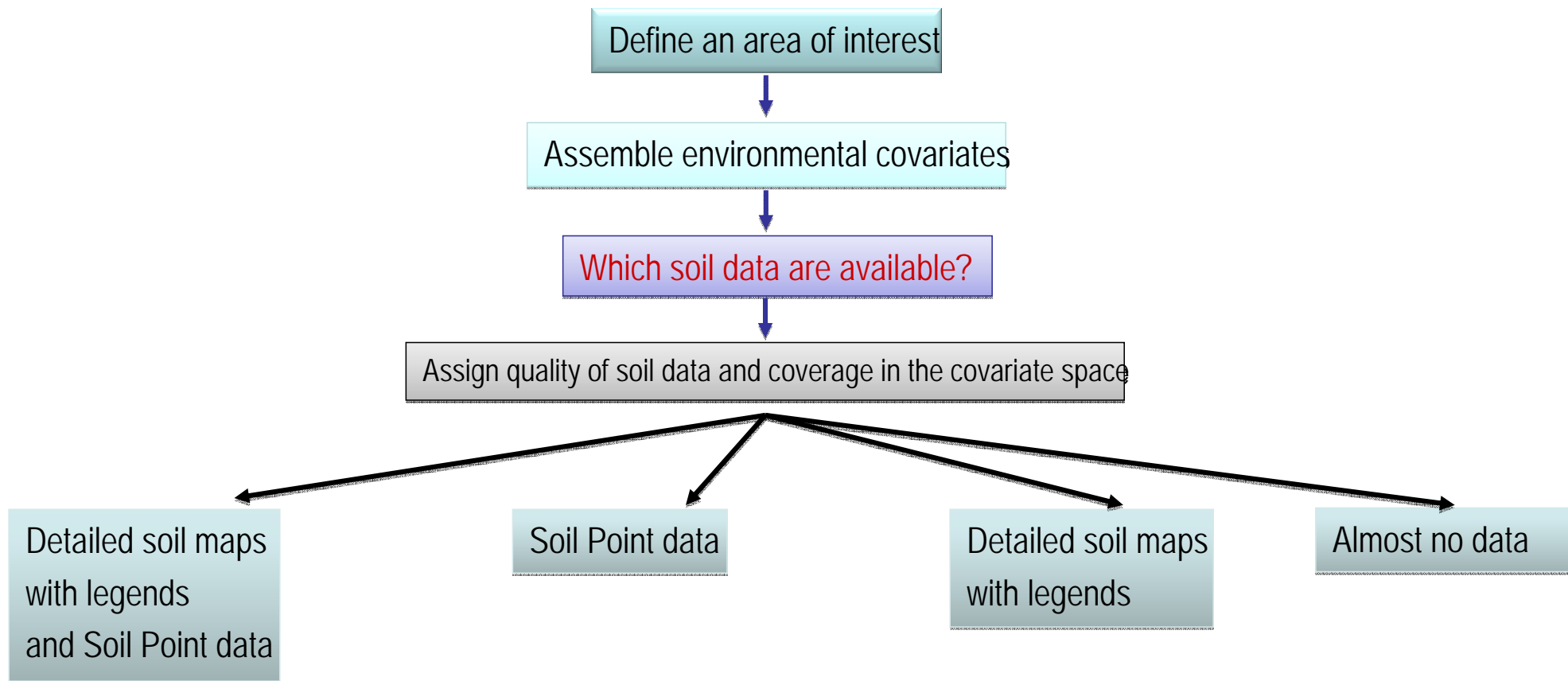
Downloaded from www.sciencemag.org on August 9, 2009

GLOBALSOILMAP





A legacy-based approach



Which soil data are available?

Assign quality of soil data and coverage in the covariate space

Detailed soil maps with legends and Soil Point data

Soil Point data

Detailed soil maps with legends

Almost no data

scorpan kriging

Extrapolation across space - Homosoil

Full Cover?

Full Cover?

Yes

No

Yes

No

Soil maps:
-Spatially weighted mean
-Spatial disaggregation
Soil data:
- *scorpan* kriging

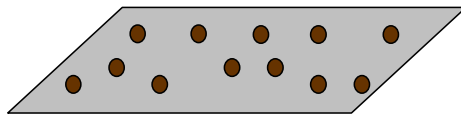
Extrapolation from reference areas:
-Soil maps
-Soil point data

-Spatially weighted mean
-Spatial disaggregation

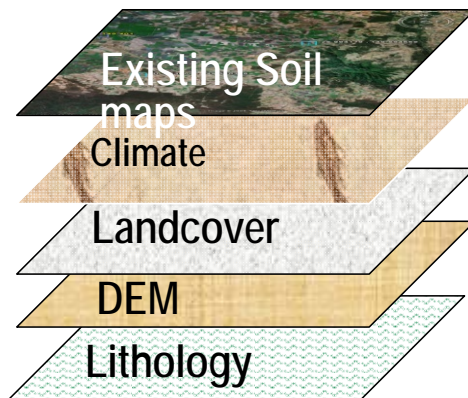
Extrapolation from reference areas
Spatially weighted mean

Lots of point data – the easiest approach

Soil observations or maps with legends



scorpan layers

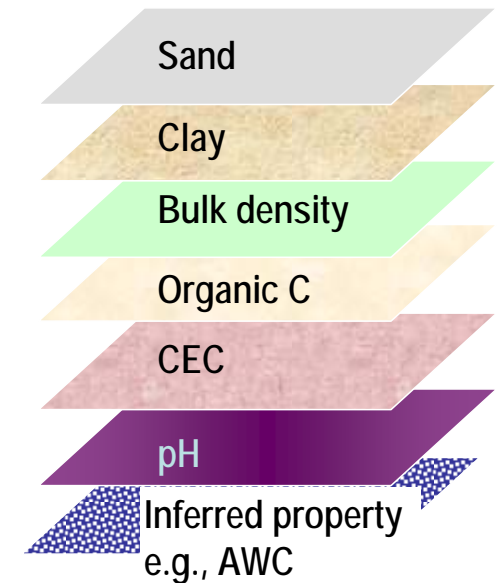


$$S = f(s, c, o, r, p, a, n) + e$$

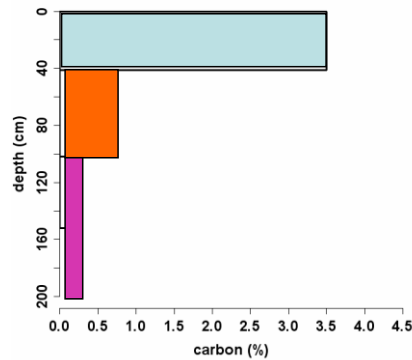
f - Linear regression,
Regression trees,
Random forests,
Neural networks,
Expert system
Etc..

Krige residuals (e)

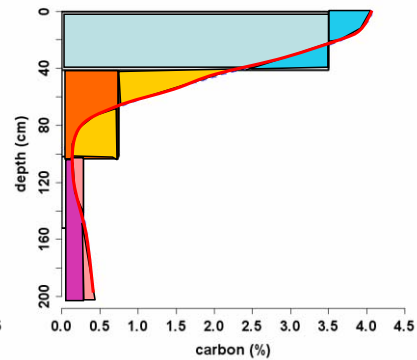
Or generalised mixed model by REML or MCMC



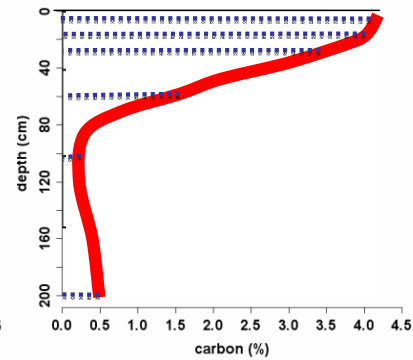
The spline and depth harmonisation



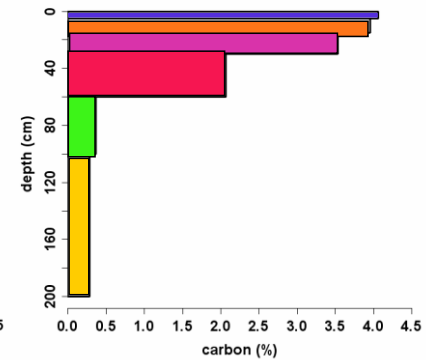
'Modal'
profile



Fit mass-
preserving
spline



Fitted
Spline



Estimate
averages for
spline at
standardised
depth ranges,
e.g.,
GlobalSoilMap
depth ranges

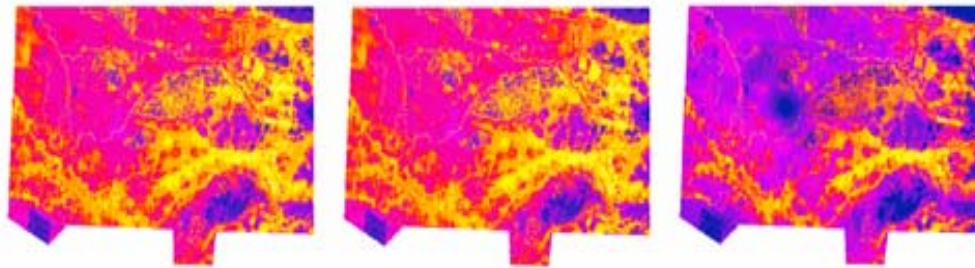
layer Soil C prediction



0-5 cm

5-15 cm

15-30 cm



30-60 cm

60-100 cm

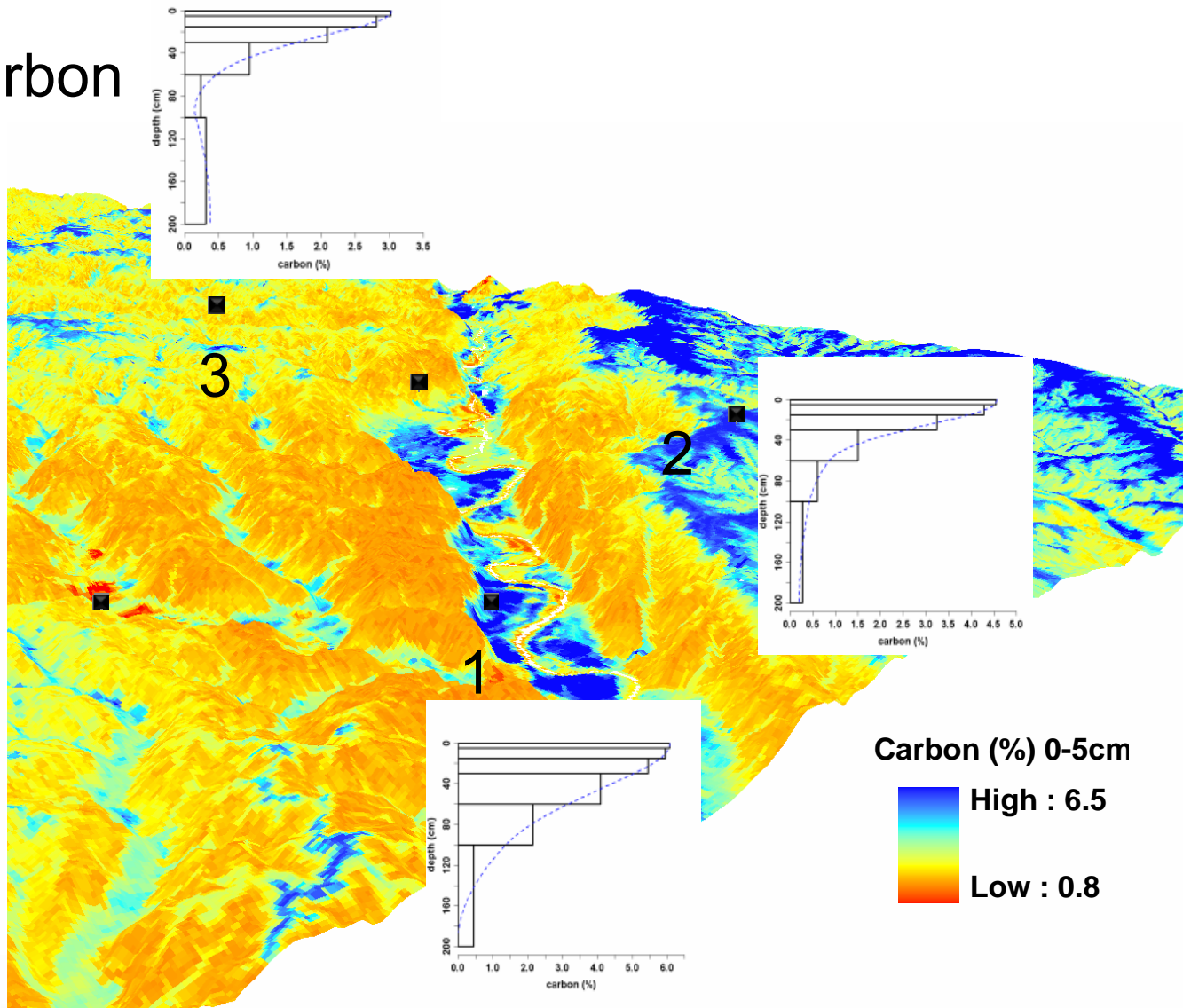
100-200 cm

Carbon Storage (kg/m³)

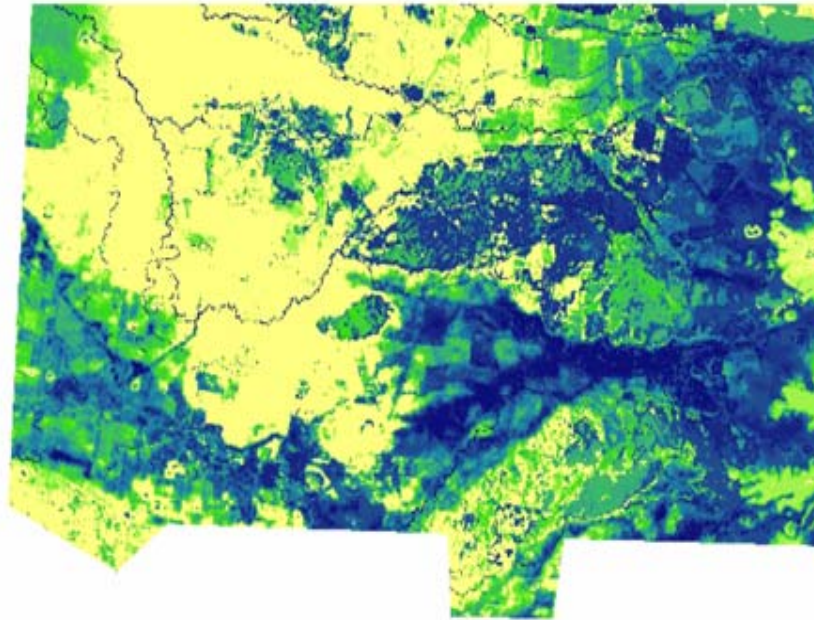


Reconstruct splines at every pixel

carbon



'Non-linear' queries

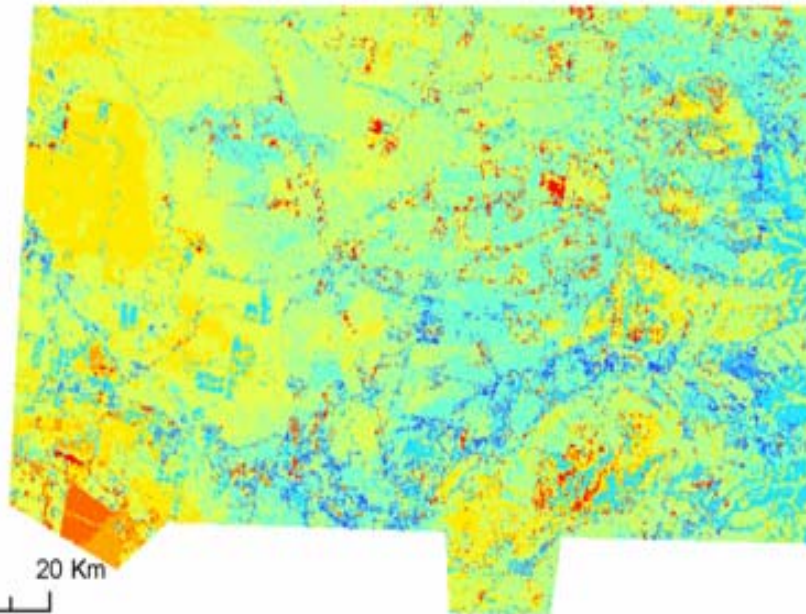


Depth (cm)

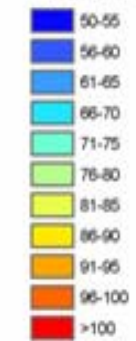


Depth at which soil C falls below 1%

c)



Depth (cm)

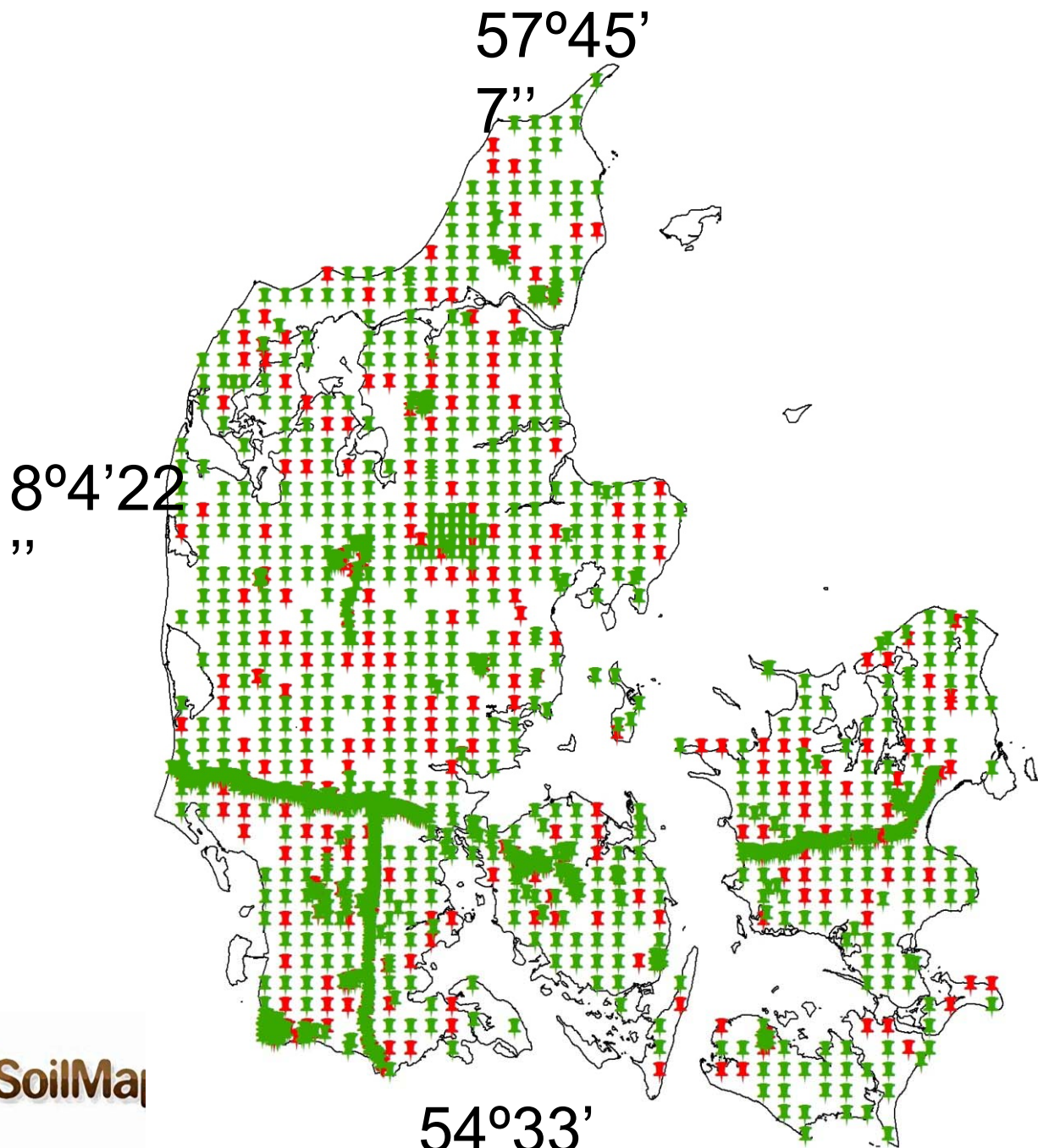


Depth at which AWC reaches 100 mm

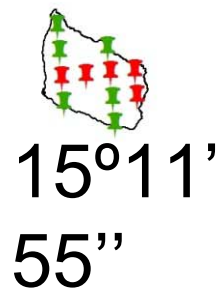


Denmark

- Mogens Greve,
Kabindra Adhikari

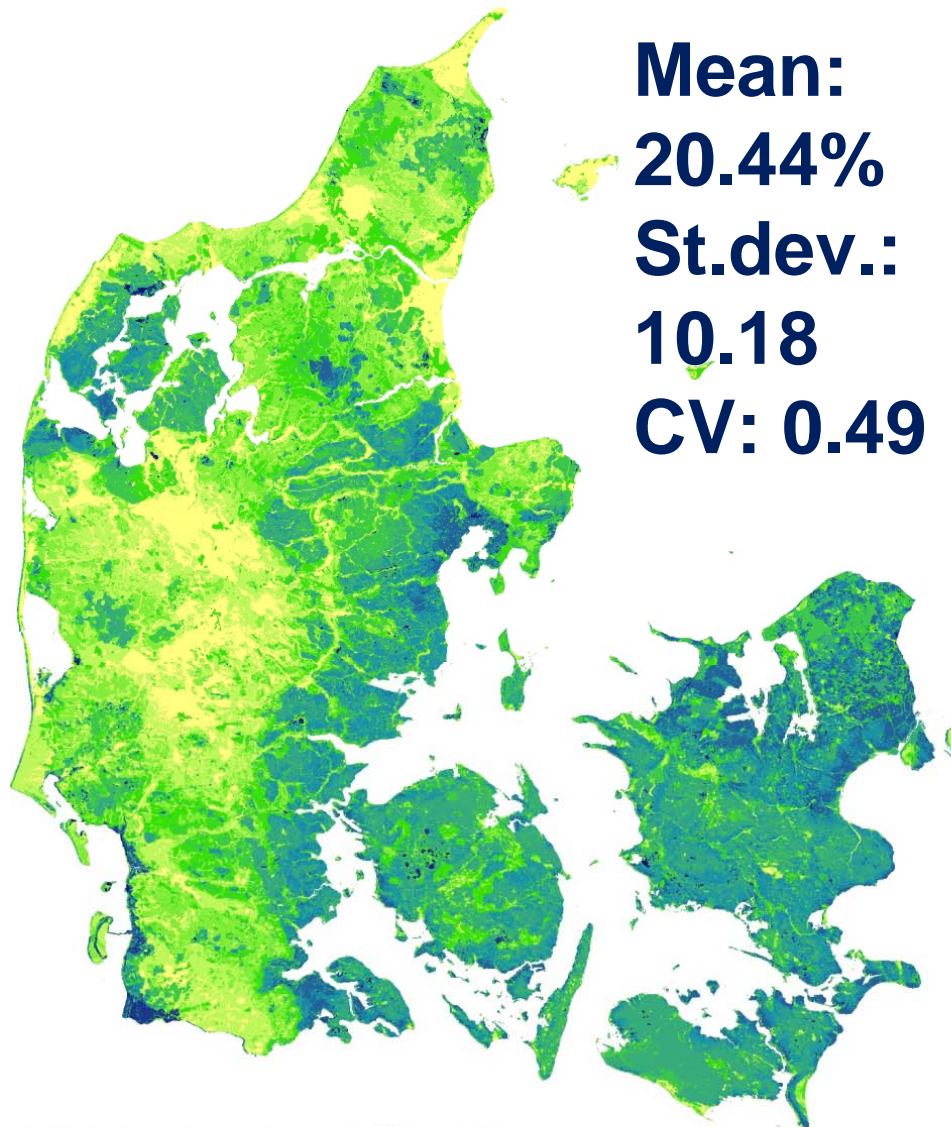


Area: 43,000 sqkm
Climate: Temperate zone
(0° to 15°C, 700mm rainfall)
Human Pop. : 5.56 M
Pigs: 12 M (2010)





Total silt content



Mean:
20.44%
St.dev.:
10.18
CV: 0.49

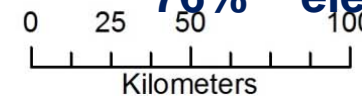


Top 3 predicting conditions

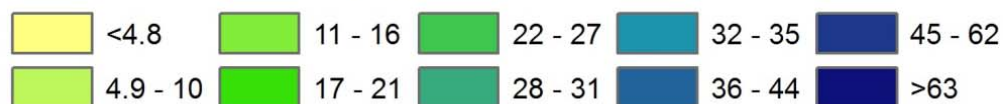
97% soilmap
89% geology_re
32% clc

Top 5 model predictors

96% horoverlan
93% mrvbf
90% slope
90% valley_dep
76% elevation

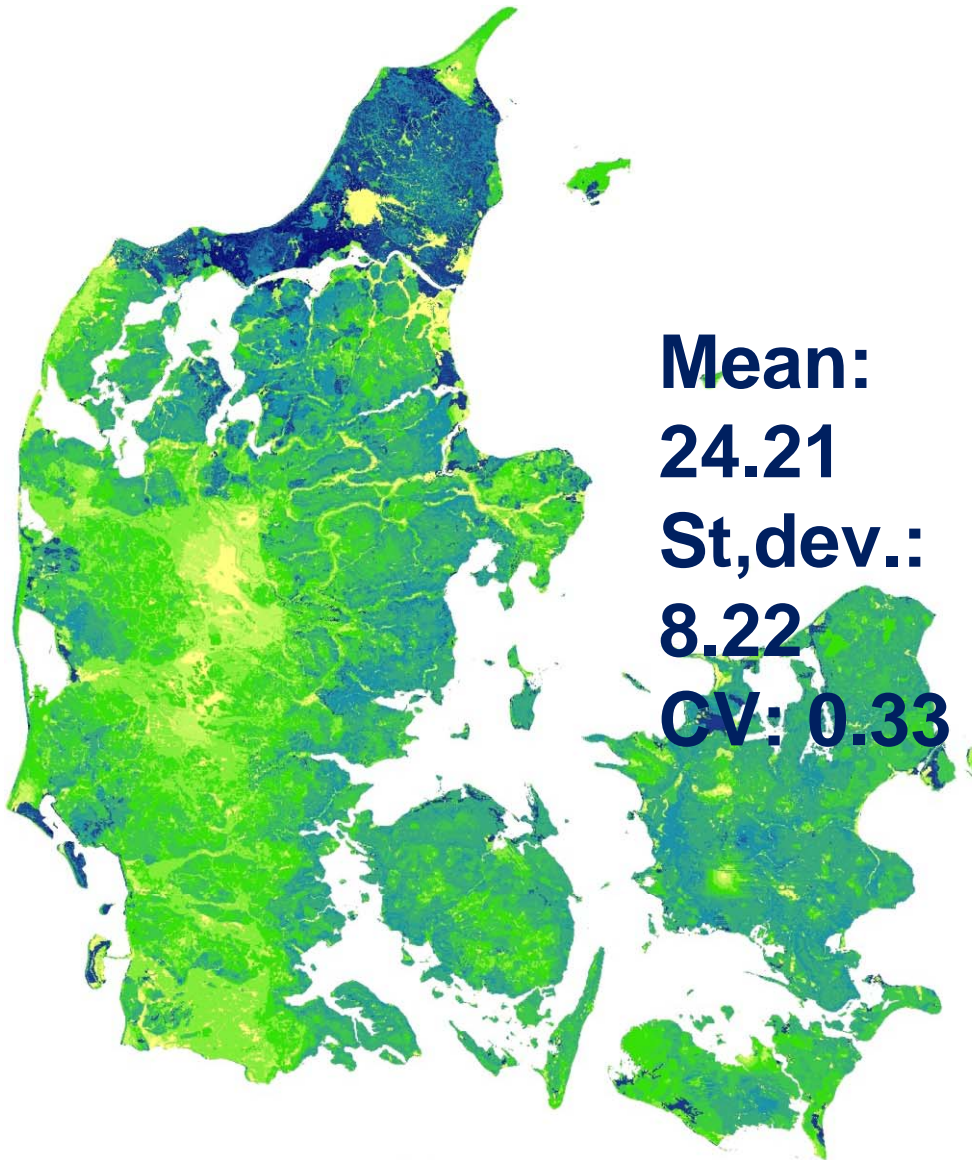


Total silt content (%)_ 0-5cm





Fine sand content



Mean:
24.21
St,dev.:
8.22
CV: 0.33



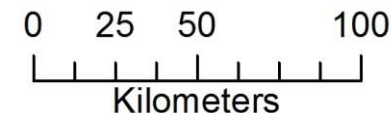
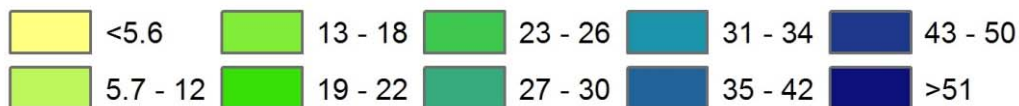
Top 3 predicting conditions

100% soilma
97% geology_re
33% clc

Top 5 model predictors

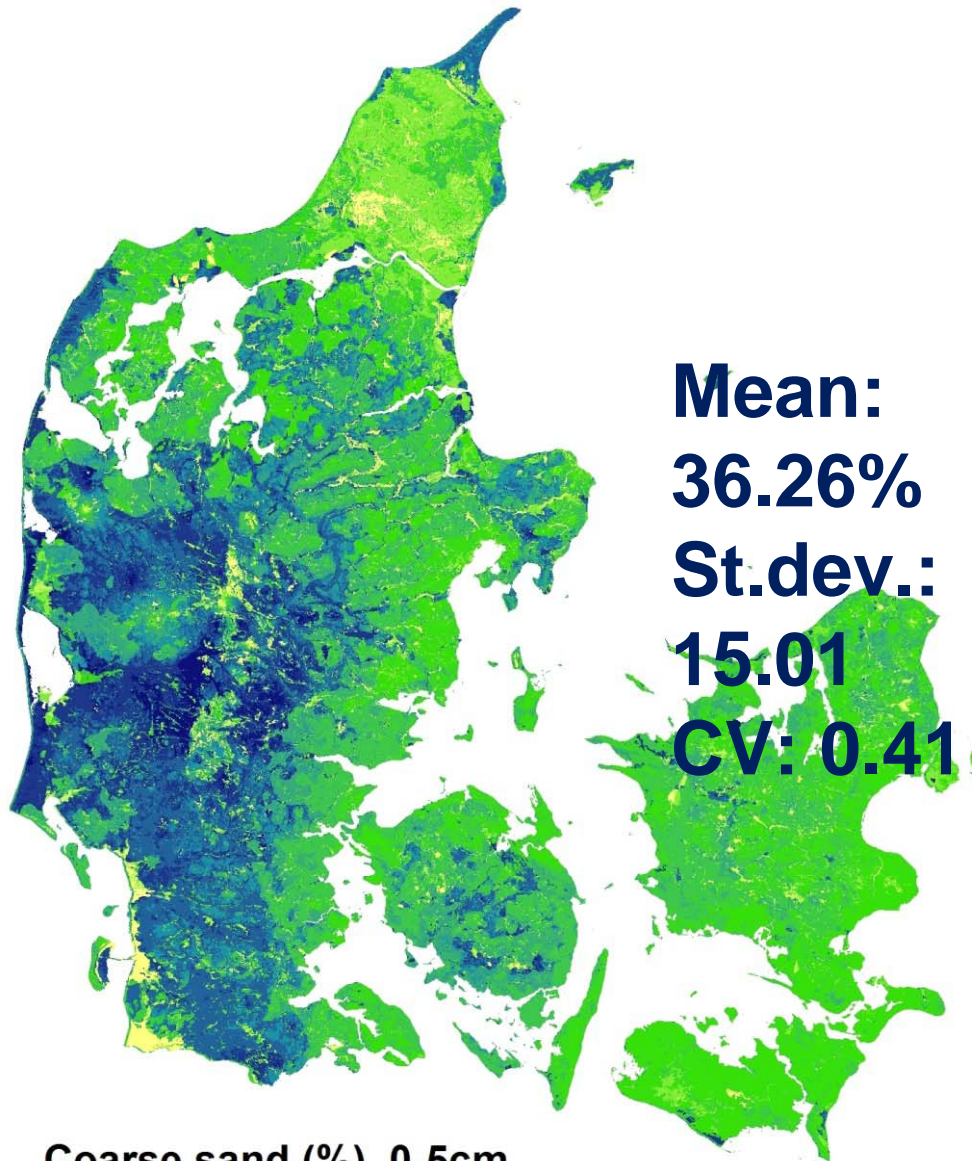
95% mrrtf
95% horoverlan
72% mrvbf
66% twi
61% elevation

Fine sand content (%)_0-5cm





Coarse sand content



Mean:
36.26%
St.dev.:
15.01
CV: 0.41



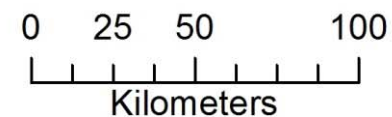
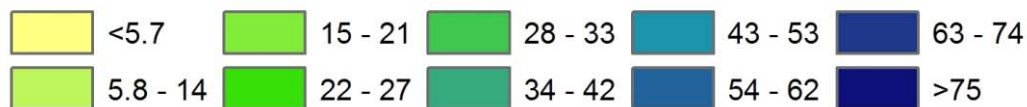
Top 3 predicting conditions

100% soilmap
45% vertdist_t
42% geology_re

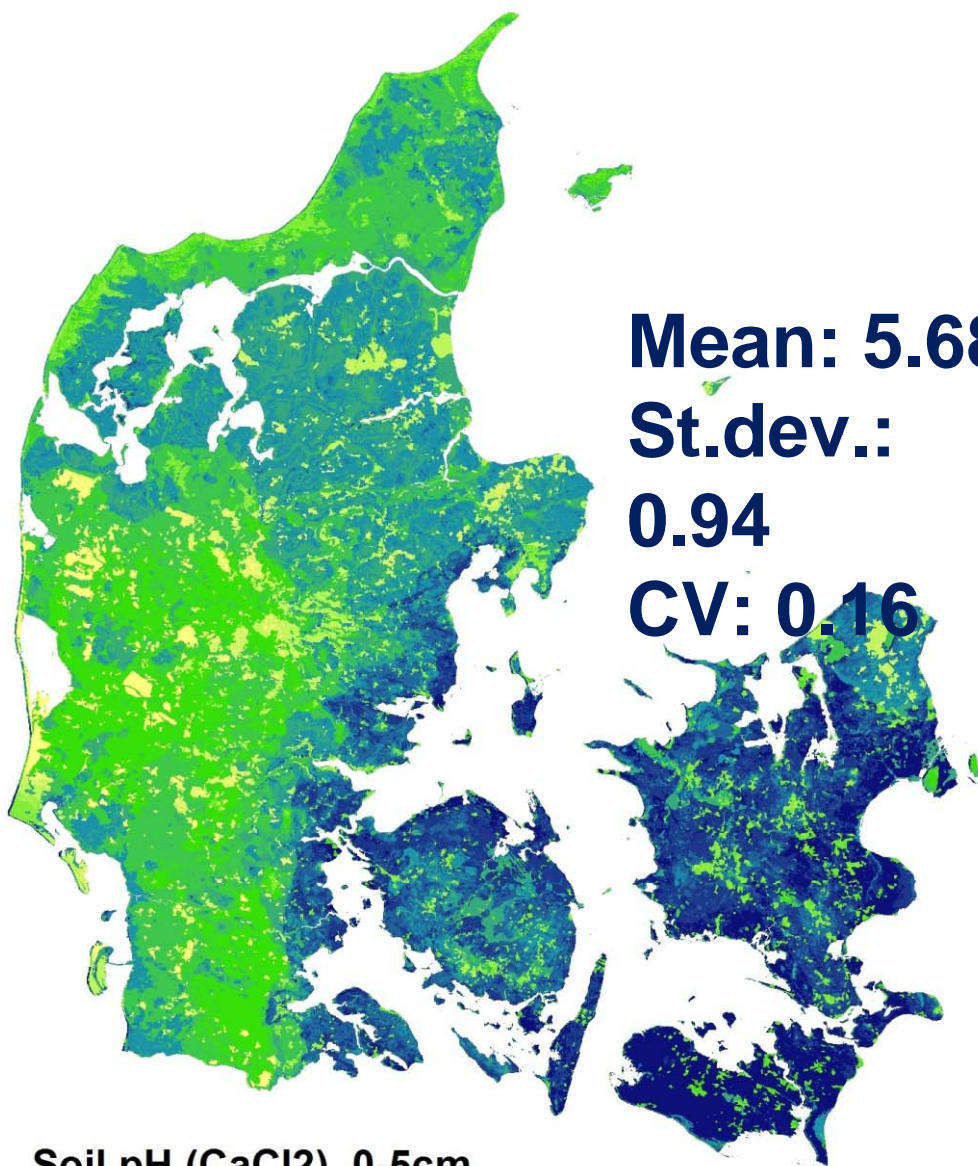
Top 5 model predictors

80% horoverlan
65% slope
55% mrvbf
49% direct_ins
47% valley_dep

Coarse sand (%)_0-5cm



Soil pH (CaCl2)



Mean: 5.68
St.dev.: 0.94
CV: 0.16



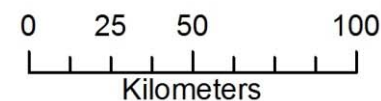
Top 3 prediction conditions

100%	clc
100%	georegions
86%	soilmap

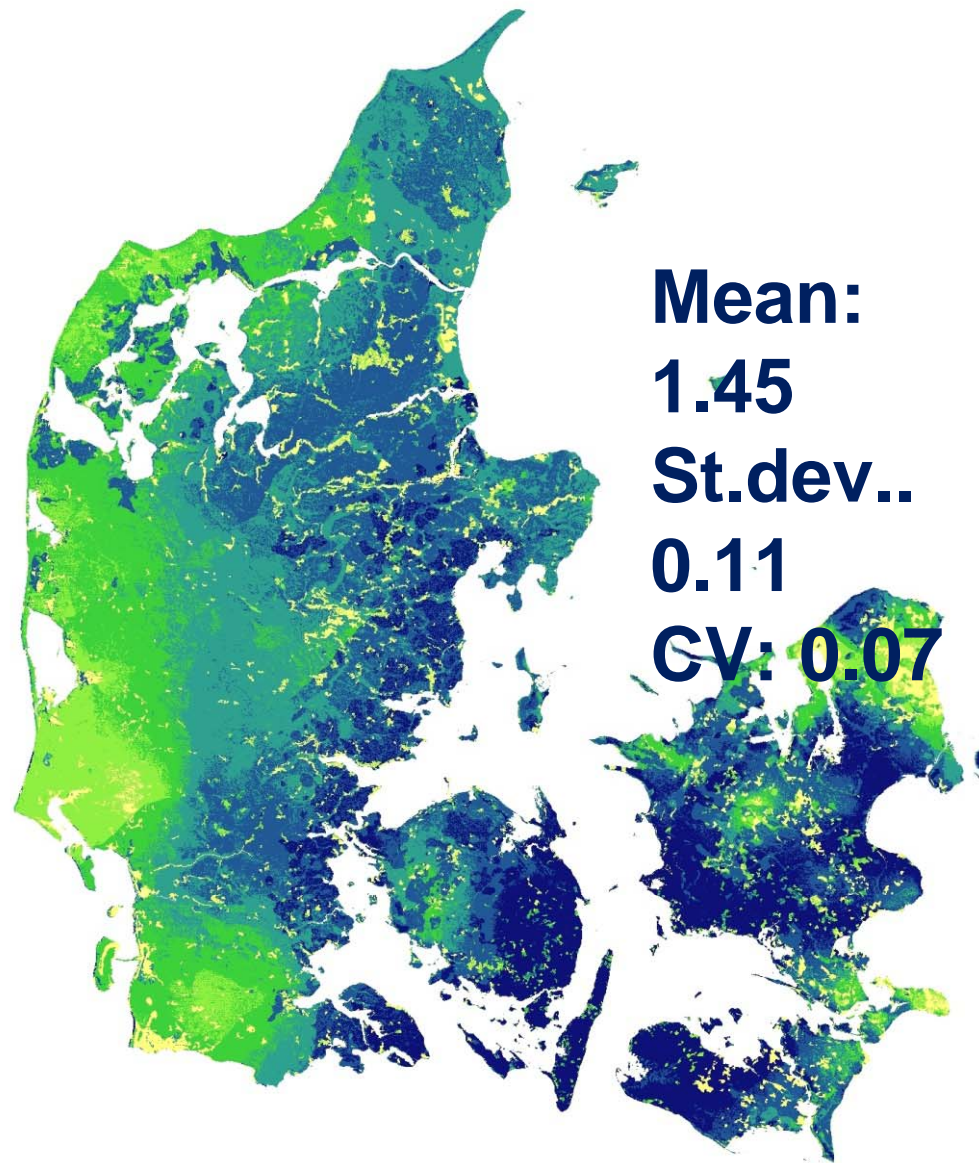
Top 5 model predictors

100%	valley_dep
91%	elevation
91%	horoverlan
91%	mrrtf
91%	mrvbf

Soil pH (CaCl2)_0-5cm



Bulk density



Mean:
1.45
St.dev.:
0.11
CV: 0.07

Top 3 predicting conditions

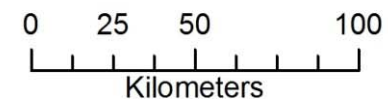
99% clc
92% elevation
92% soilmap

Top 5 model predictors

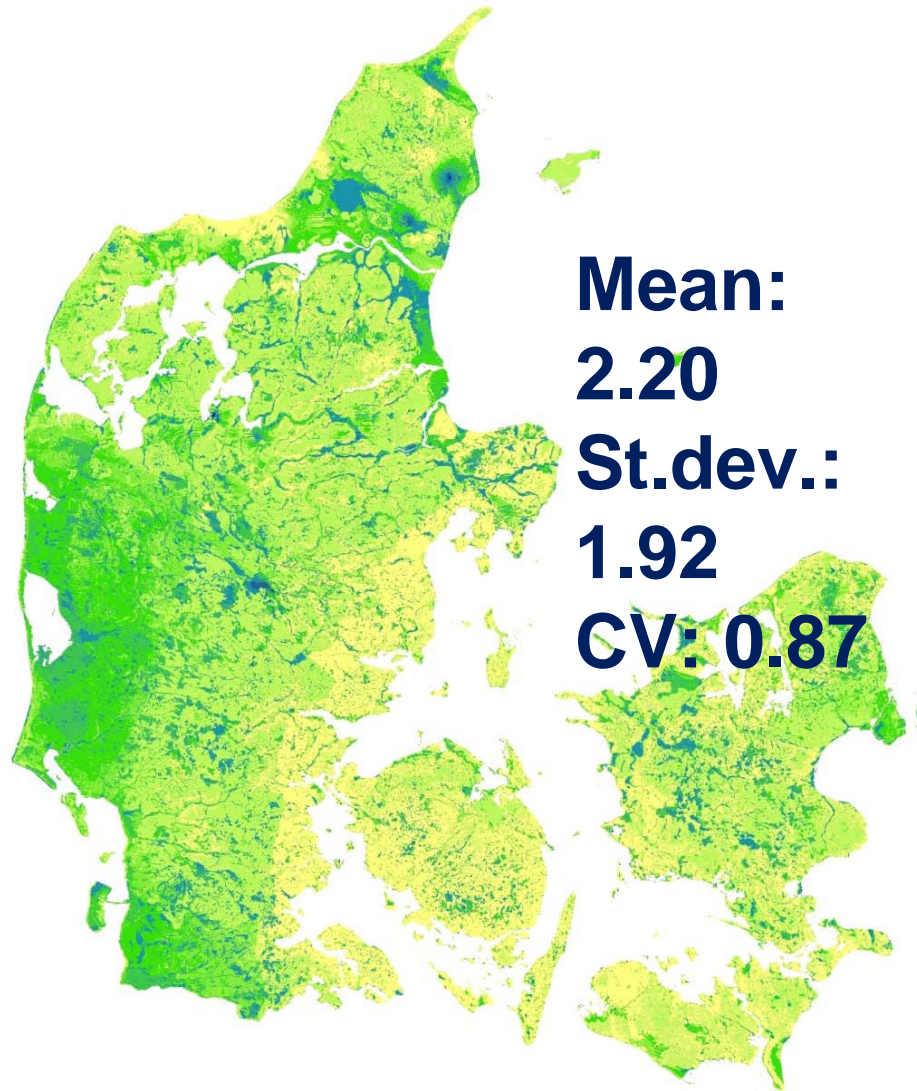
90% vertdist_t
89% slope
89% tw
75% mrrtf
55% mrvbf



Bulkdensity (gcm-3)_0-5cm



Soil organic carbon content



Mean:
2.20
St.dev.:
1.92
CV: 0.87

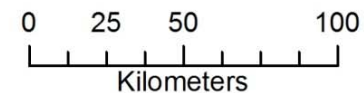


Top 3 predicting conditions

98% wetlands
84% clc
72% georegions

Top 5 model predictors

100% elevation
100% mrrtf
100% mrvbf
88% slope
77% twi

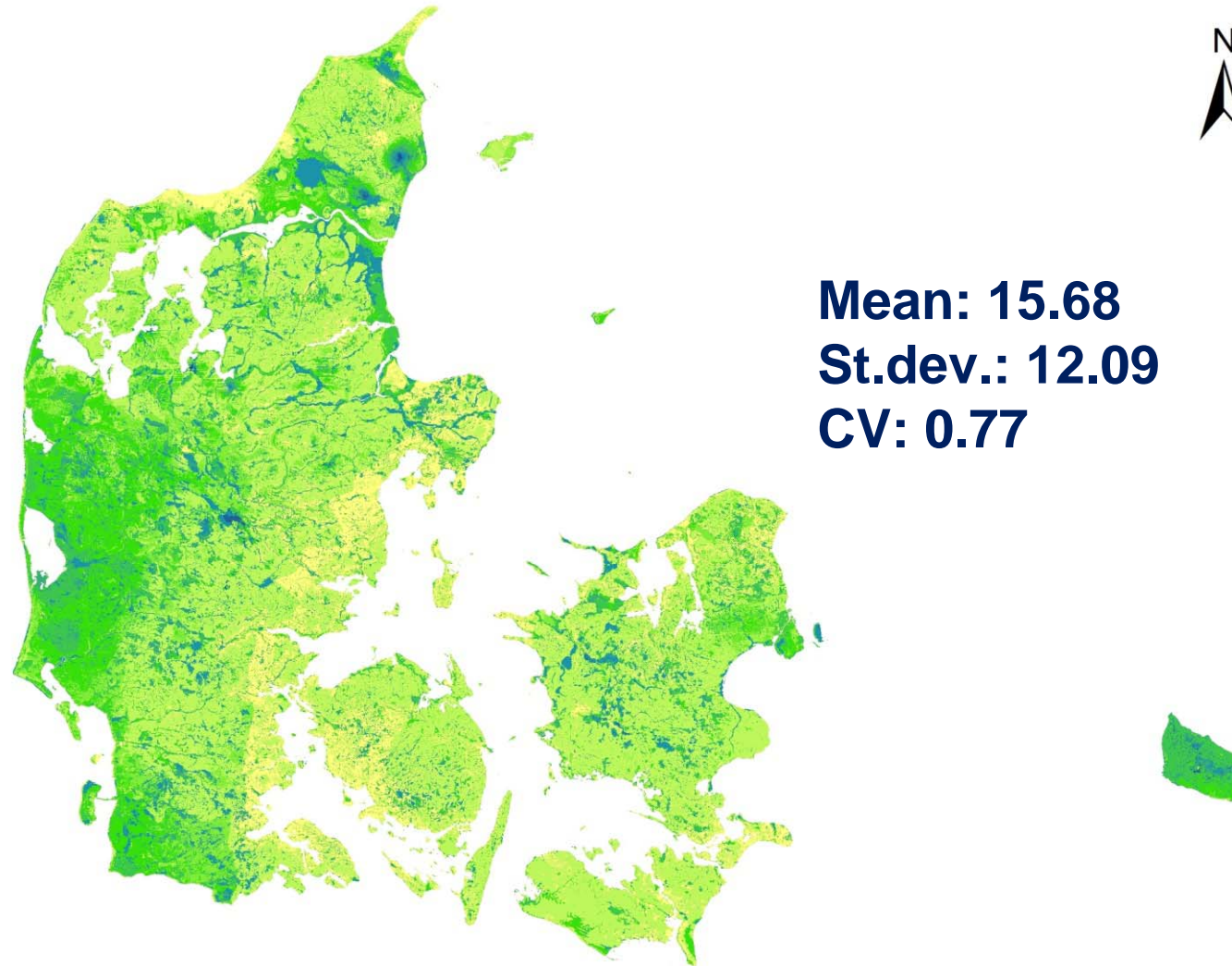


SOC (%)_0-5cm



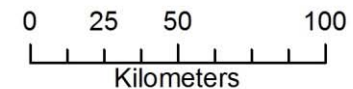
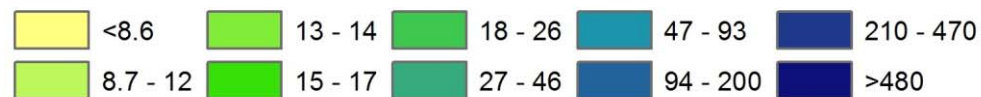
Carbon density (CD)

$$\text{CD (T/ha)} = \text{SOC\%} * \text{Bulk density (gcm}^{-3}\text{)} * \text{soil thickness (m)} * 100$$



Mean: 15.68
St.dev.: 12.09
CV: 0.77

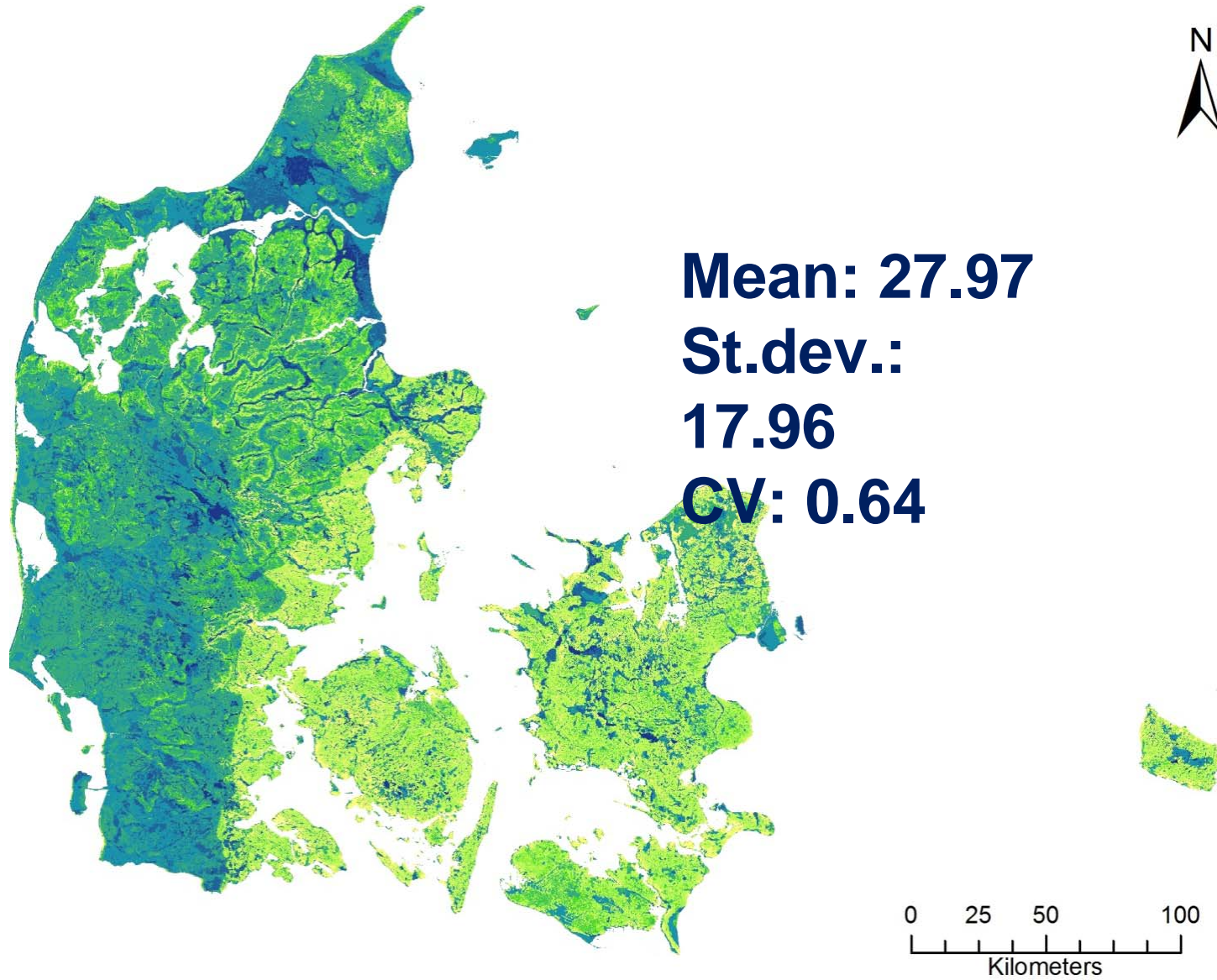
SOC density (t/ha)_0-5cm



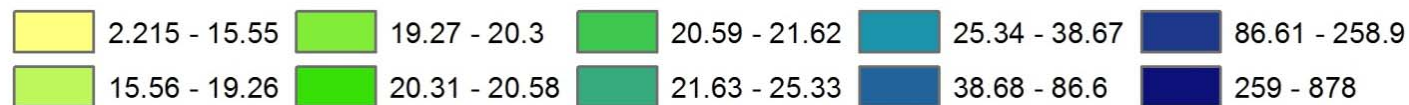
Variations of CD at different soil depths

Depth (cm)	Mean	Std.dev.	CV
0-5	15.68	12.09	0.77
5-10	13.16	8.19	0.62
10-20	24.93	15.98	0.64
20-30	20.62	33.38	1.61
30-50	24.21	28.1	1.16
50-70	36.23	49.19	1.35
70-100	79.07	42.53	0.53

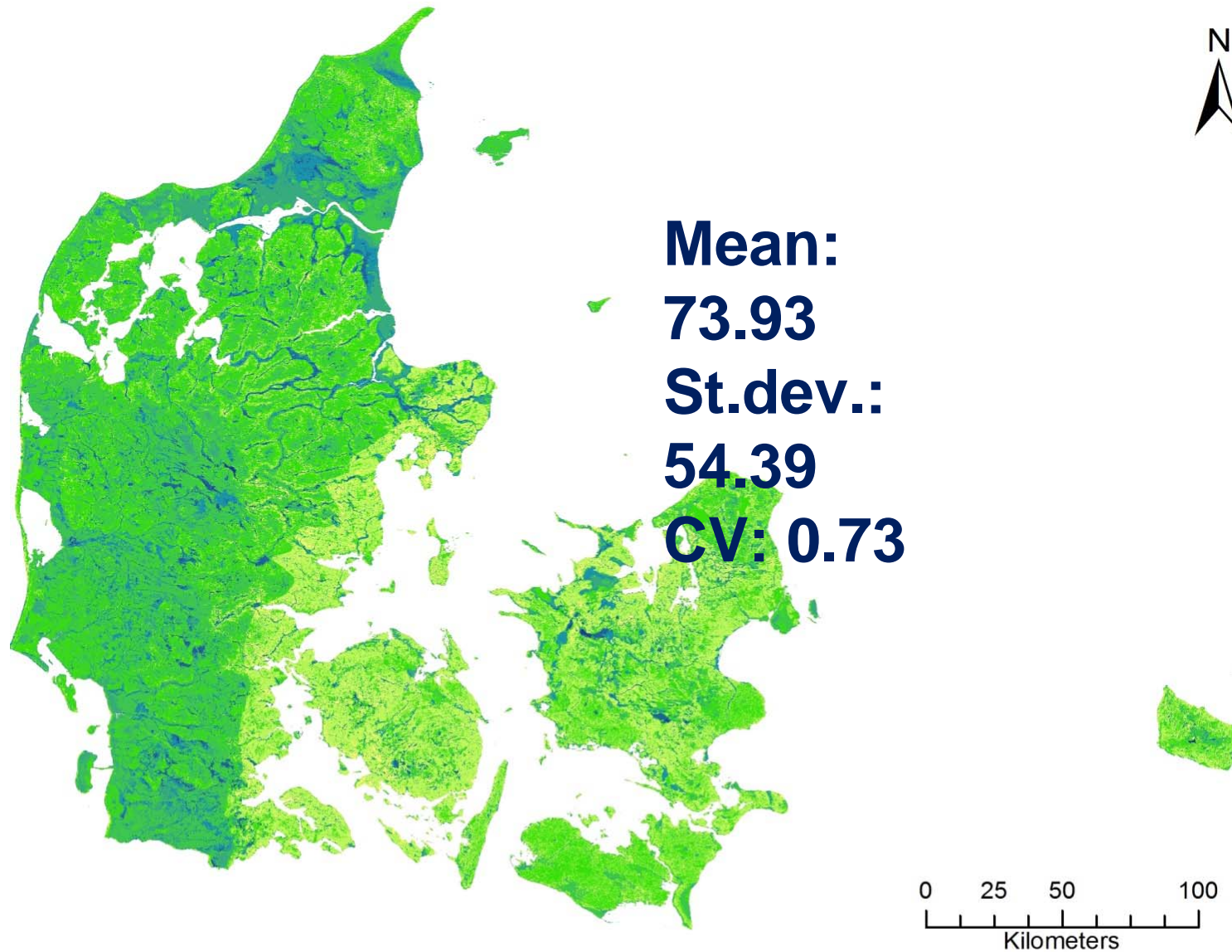
Carbon Stock 0-10cm



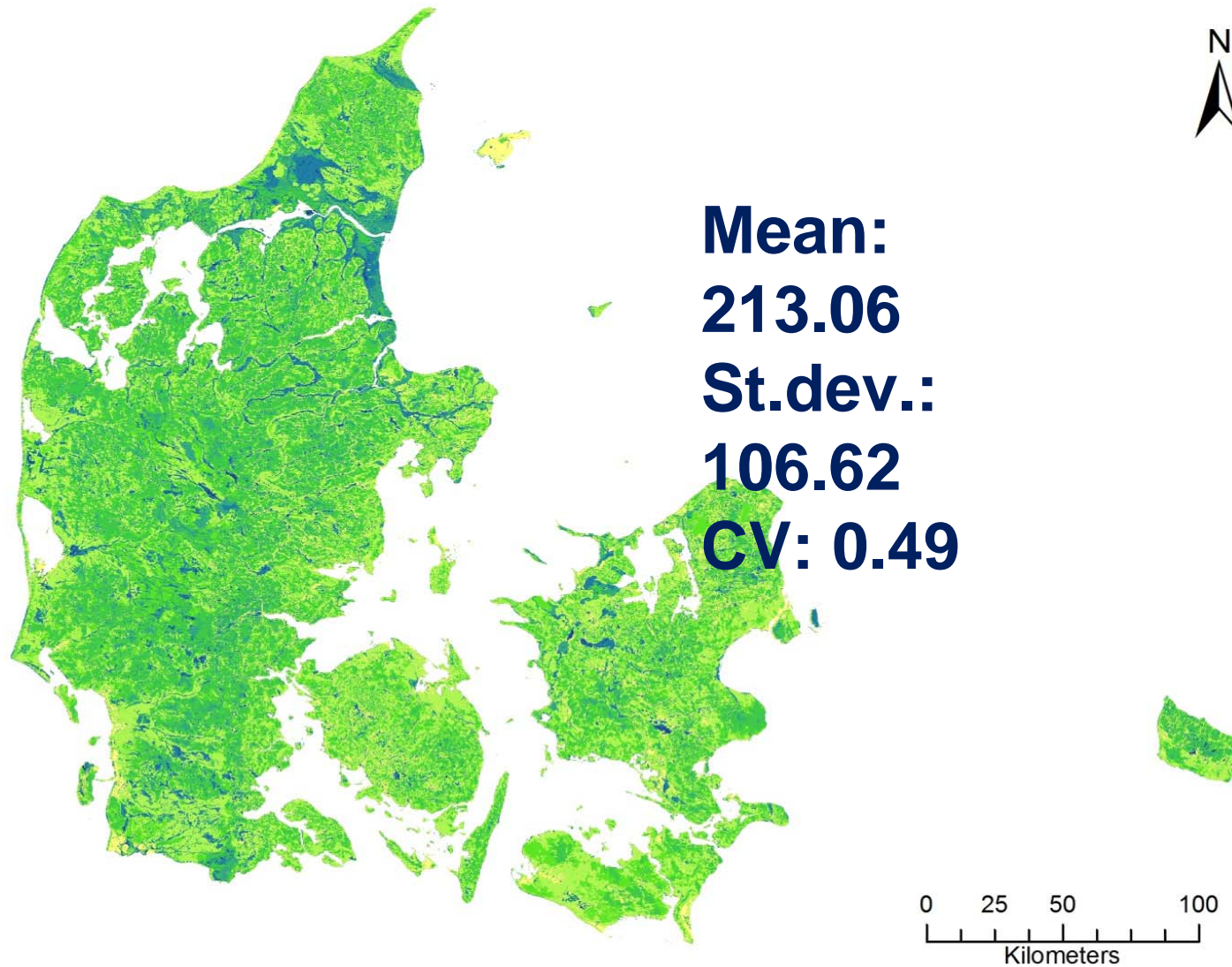
SOC stock (t/ha)_0-10cm



Carbon Stock 0-30cm



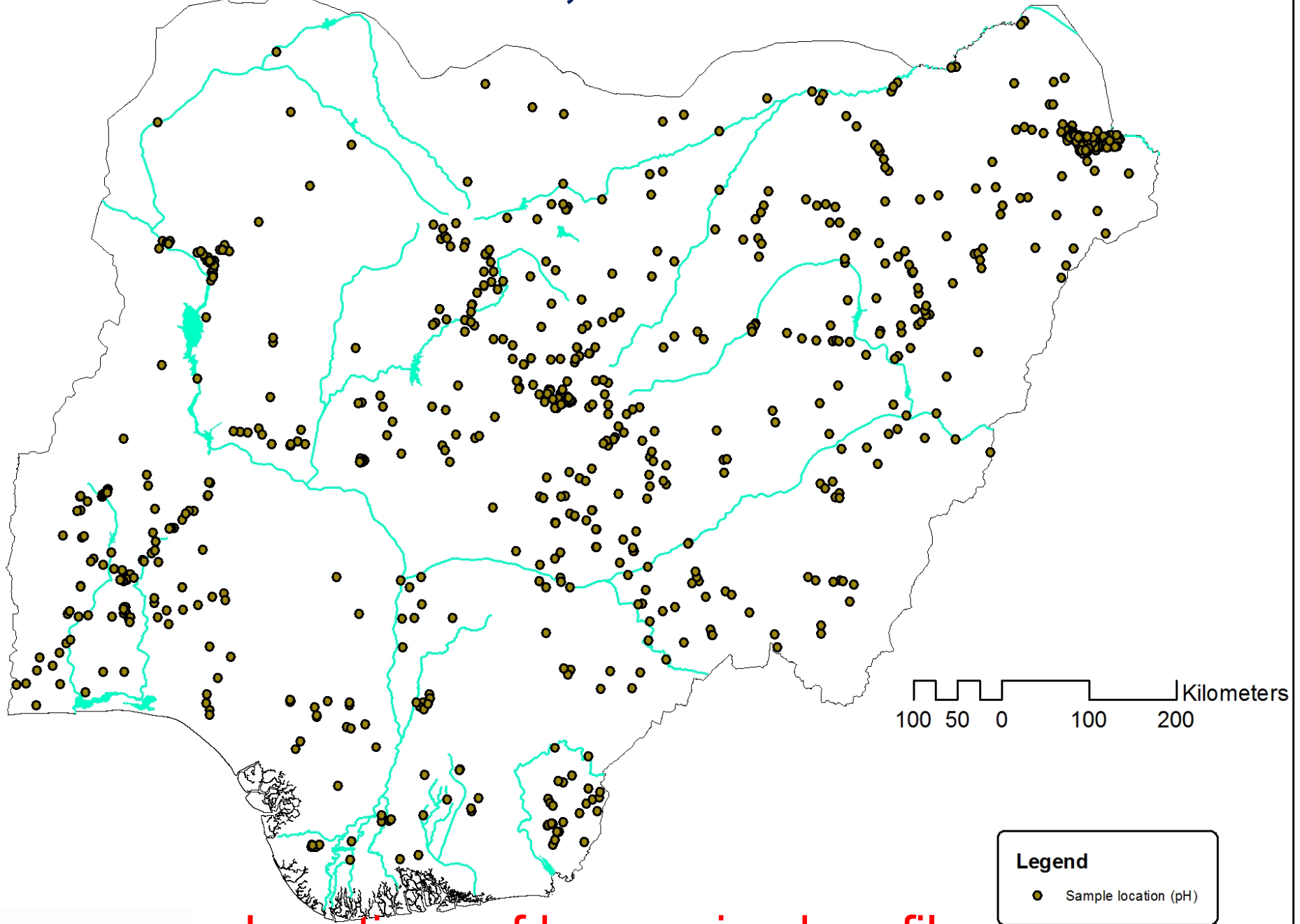
Carbon Stock to 1 m

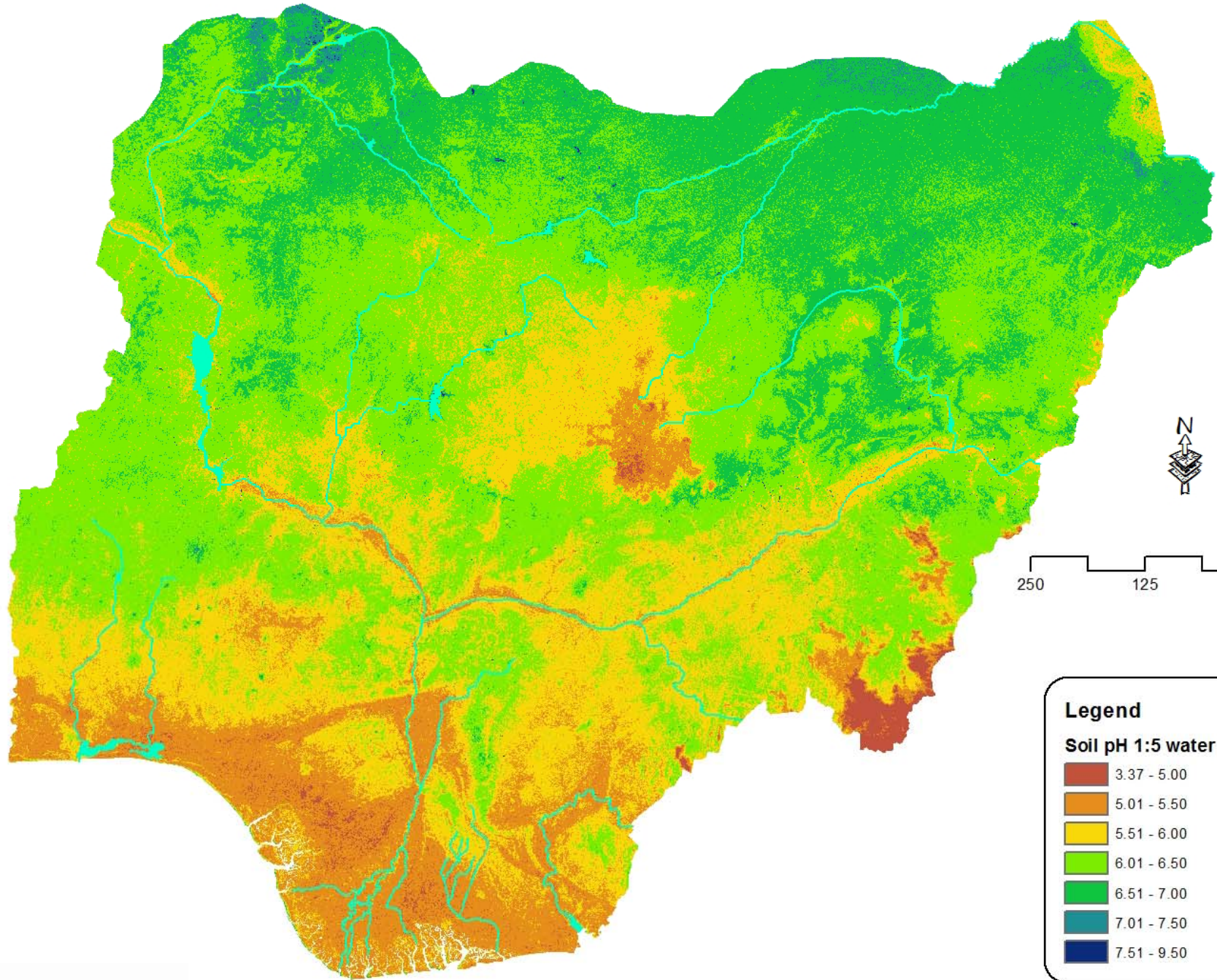


SOC stock (t/ha)_0-100cm



Nigeria - Inakwu Odeh, Hannes Reuter

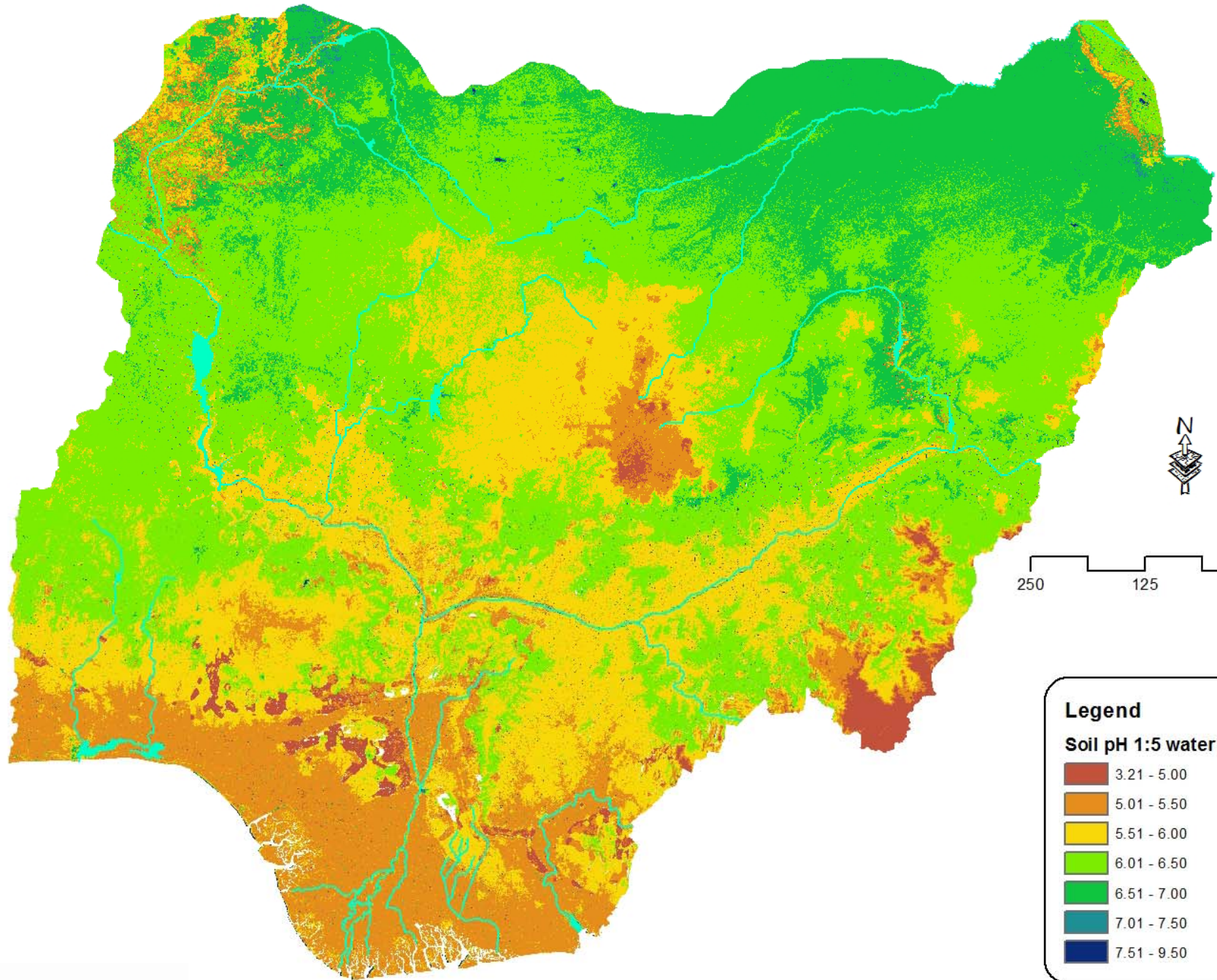




Legend








Soil pH 1:5 water (0-5 cm)

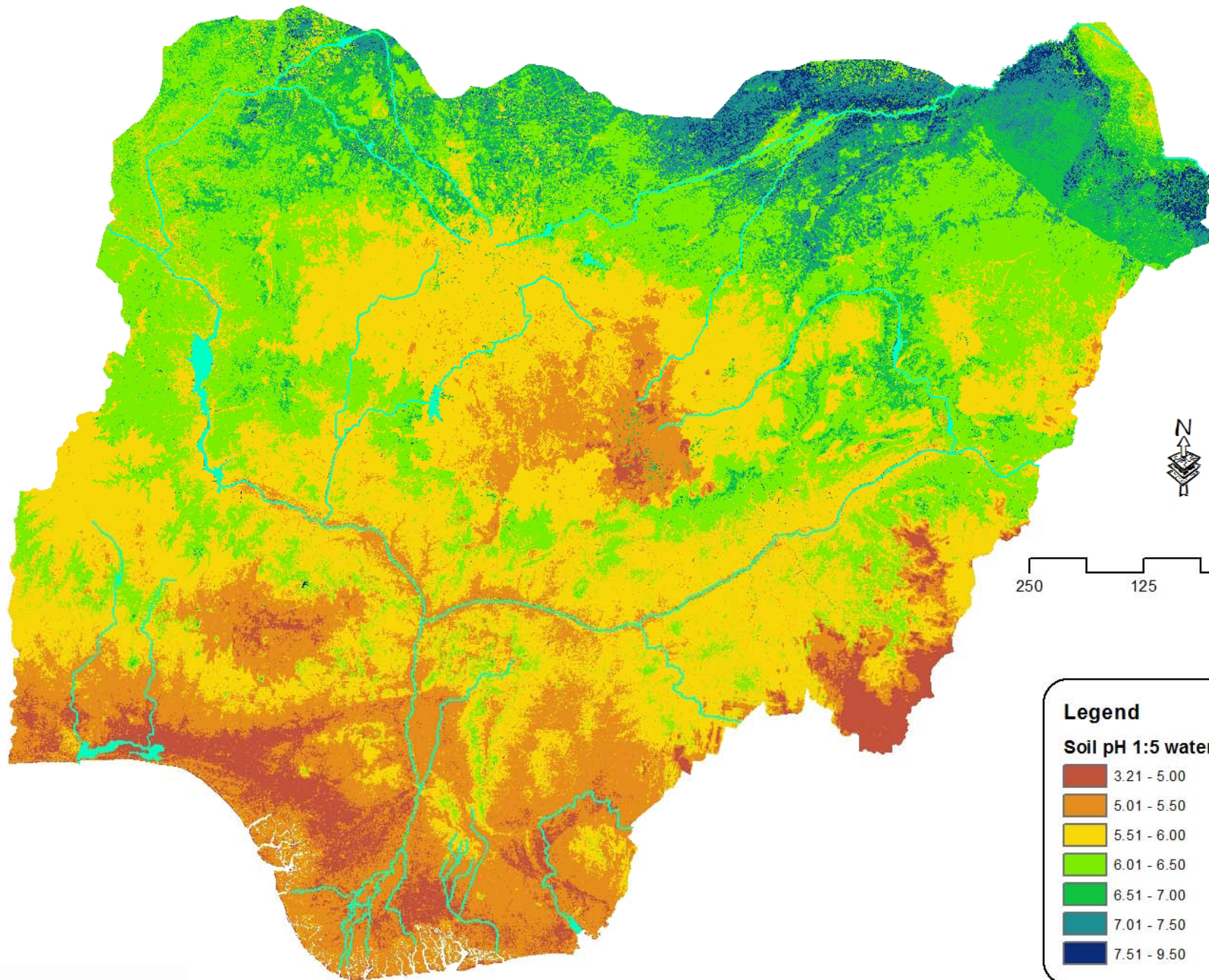
- 3.37 - 5.00
- 5.01 - 5.50
- 5.51 - 6.00
- 6.01 - 6.50
- 6.51 - 7.00
- 7.01 - 7.50
- 7.51 - 9.50



Legend

Soil pH 1:5 water (5-15 cm)

-  3.21 - 5.00
-  5.01 - 5.50
-  5.51 - 6.00
-  6.01 - 6.50
-  6.51 - 7.00
-  7.01 - 7.50
-  7.51 - 9.50

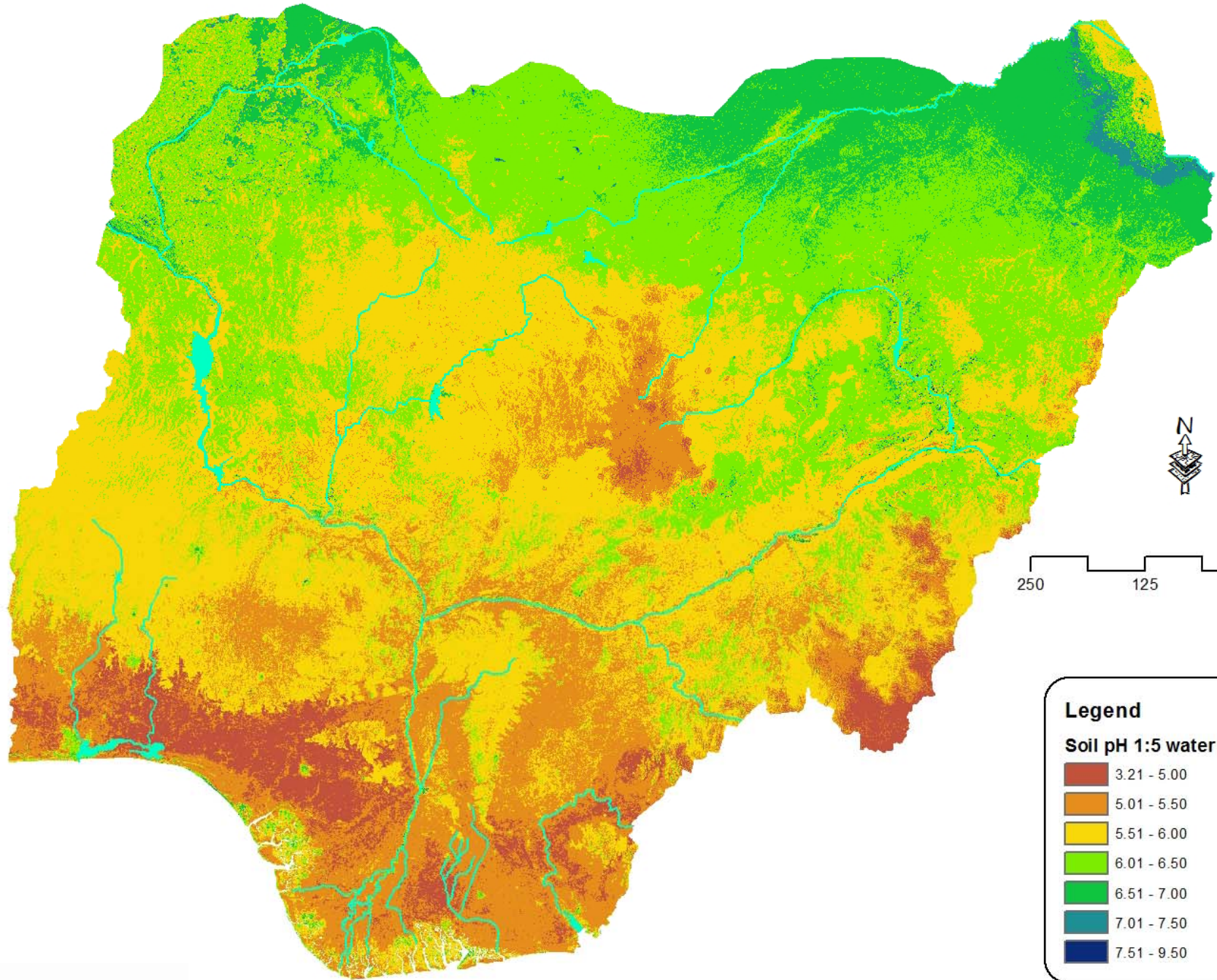


250 125 0 Kilometers

Legend

Soil pH 1:5 water (15-30 cm)

- 3.21 - 5.00
- 5.01 - 5.50
- 5.51 - 6.00
- 6.01 - 6.50
- 6.51 - 7.00
- 7.01 - 7.50
- 7.51 - 9.50

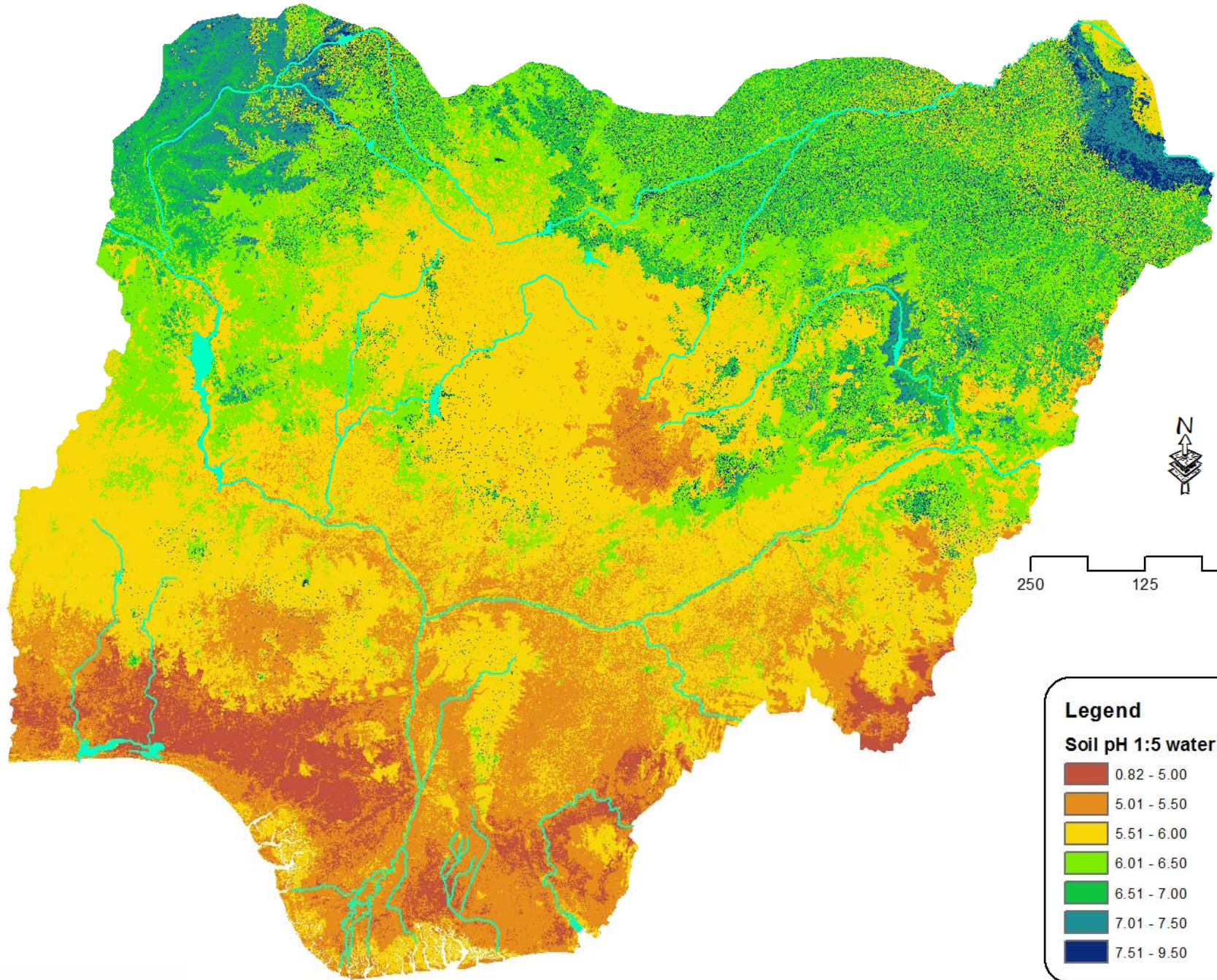


250 125 0 Kilometers

Legend

Soil pH 1:5 water (30-60 cm)

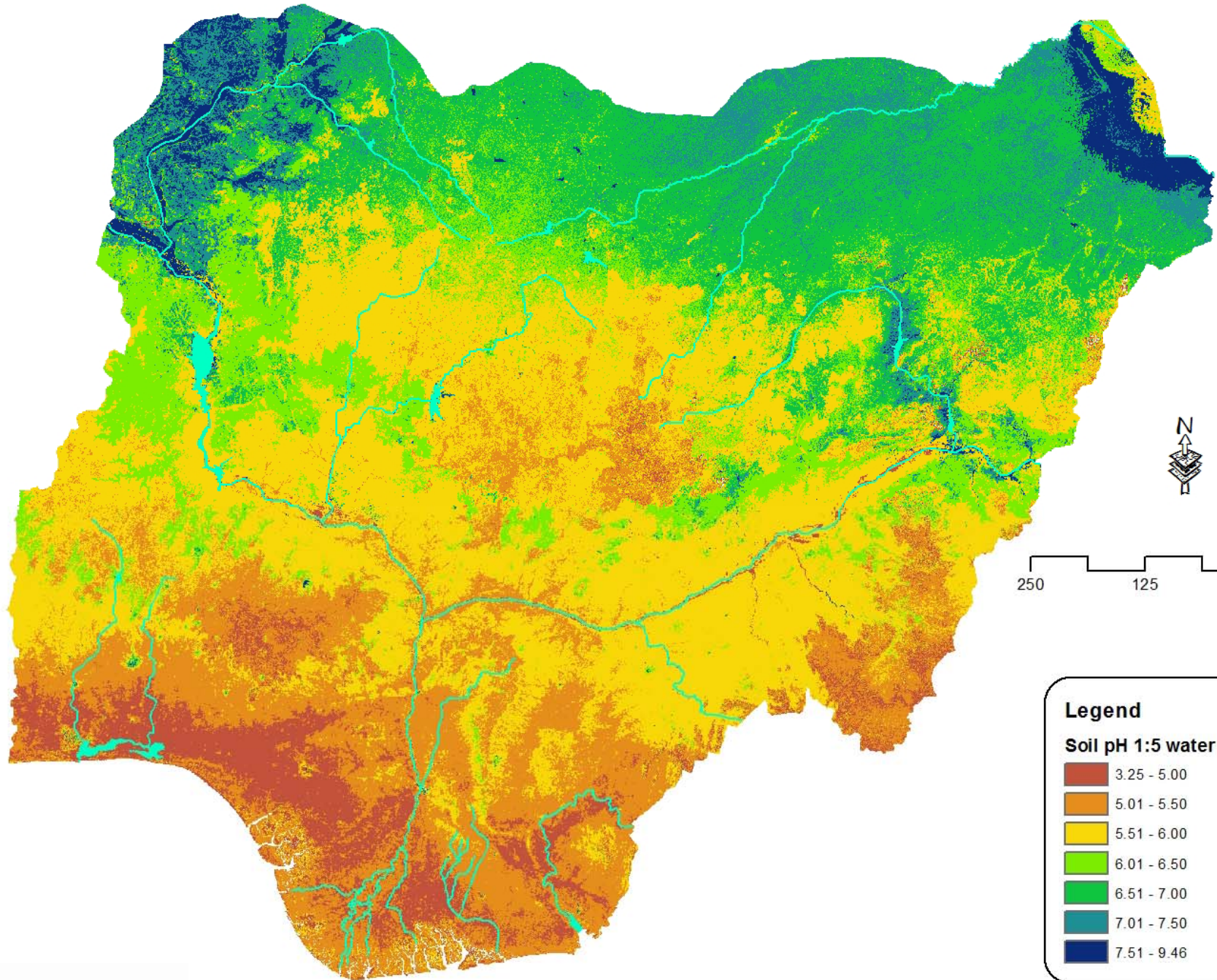
3.21 - 5.00
5.01 - 5.50
5.51 - 6.00
6.01 - 6.50
6.51 - 7.00
7.01 - 7.50
7.51 - 9.50



250 125 0 Kilometers








Legend
Soil pH 1:5 water (60-100 cm)

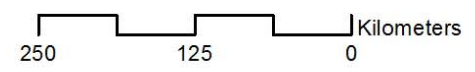
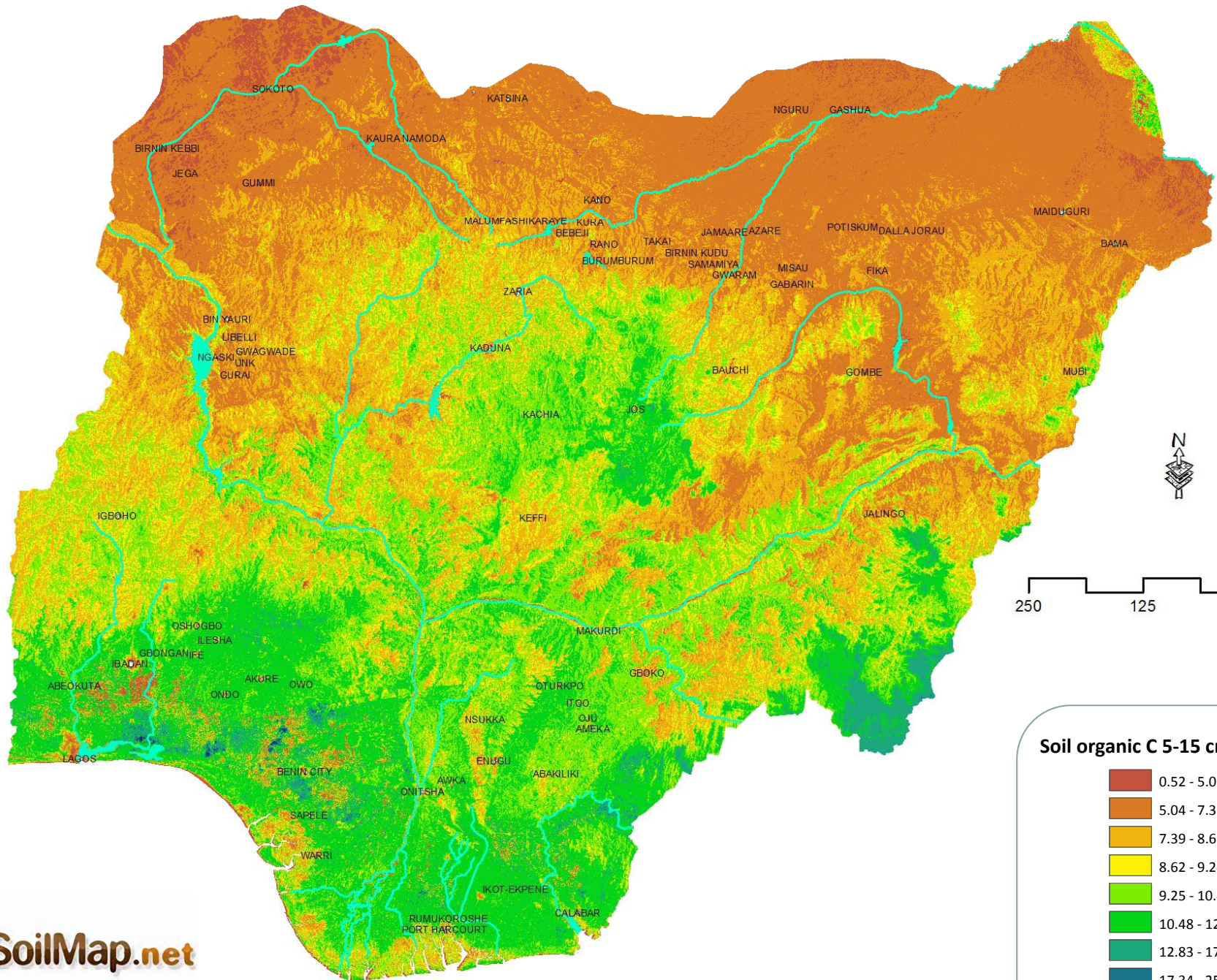
0.82 - 5.00
5.01 - 5.50
5.51 - 6.00
6.01 - 6.50
6.51 - 7.00
7.01 - 7.50
7.51 - 9.50



Legend

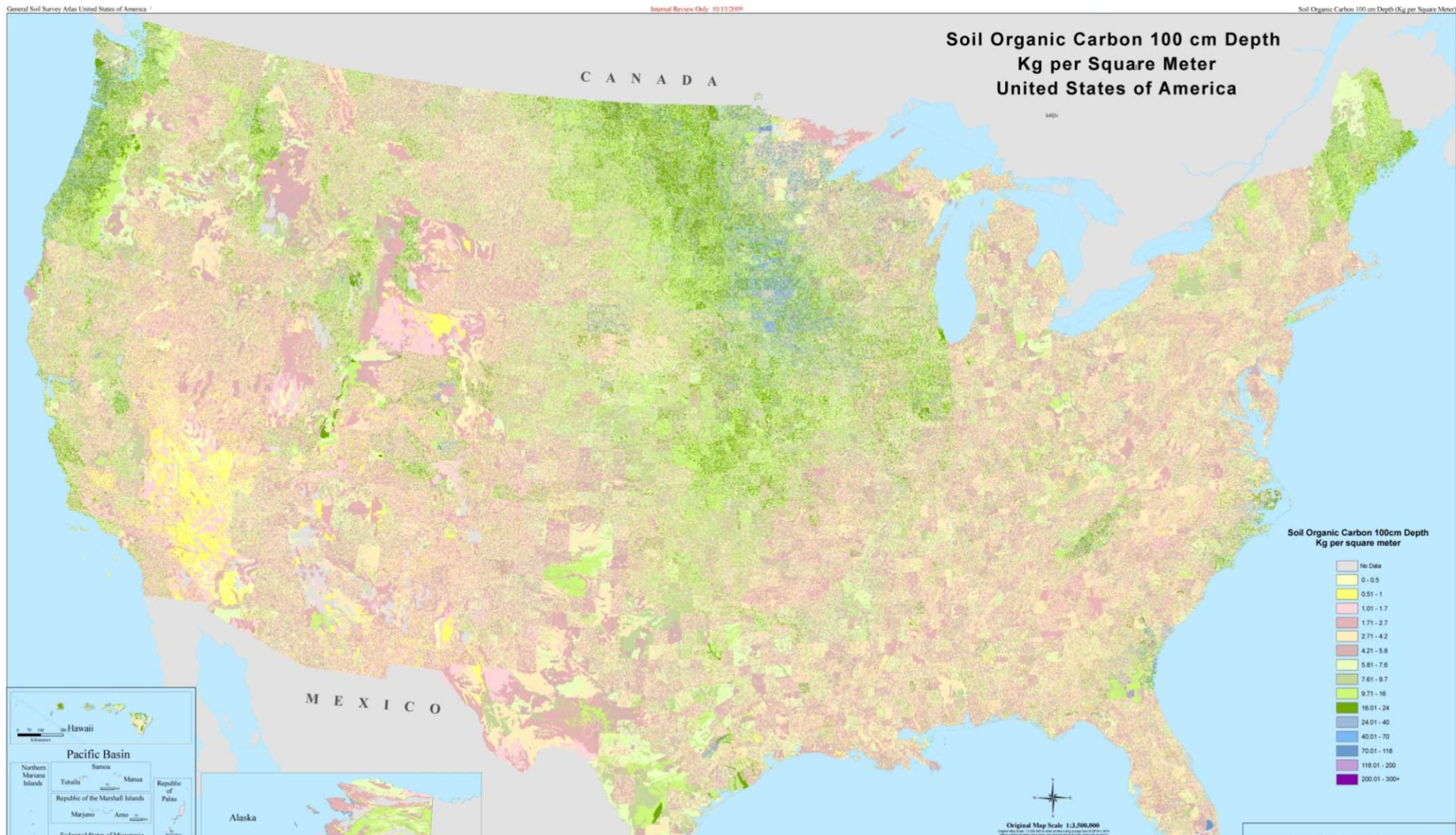
Soil pH 1:5 water (100-200 cm)

-  3.25 - 5.00
-  5.01 - 5.50
-  5.51 - 6.00
-  6.01 - 6.50
-  6.51 - 7.00
-  7.01 - 7.50
-  7.51 - 9.46



Soil organic C 5-15 cm (g/kg)

- 0.52 - 5.03
- 5.04 - 7.38
- 7.39 - 8.61
- 8.62 - 9.24
- 9.25 - 10.47
- 10.48 - 12.82
- 12.83 - 17.33
- 17.34 - 25.99
- 26.00 - 42.62



Detailed soil survey polygon data (SSURGO) and generalized polygon data (STATSGO) were converted to raster based information for cumulative organic carbon data to

100 cm depth

Capacity Building DSM

Curriculum

Prior - Soil Science & cognate disciplines

Digital soil mapping

- legacy soil data, soil data models
- covariates, prediction methods,
- uncertainty analysis
- spatial information systems

Digital soil assessment

- soil functions, threats to soil
- soil ecosystem goods & services
- financial, production, & ecosystem risk



How many DSMers?

YEAR	POPULATION	No SOIL SCIENTISTS	No DIGITAL SOIL MAPPERS
2012	7 000 000 000	50 000	~100-200
2062	9 500 000 000	80 000	2 000-10 000

In the next 5 years we need to train several hundred (500)

GlobalSoilMap Organisational Concepts

GLOBAL Consortium

Nodes - work and capacity-building

Working groups

Scientific coordination

GlobalSoilMap Scientific Concepts

GLOBAL

Recognition of legacy data

Key soil properties

Fixed depths and spline model

Quantitative uncertainty

Resolution ~100 m

Variety of prediction methods

GlobalSoilMap Particular Successes so far

Nodes

Legacy data capture and recognition

The splines

Weighted mean estimates

Some training

Challenges

Disaggregation models

Uncertainty estimates

Acceptable PTFs

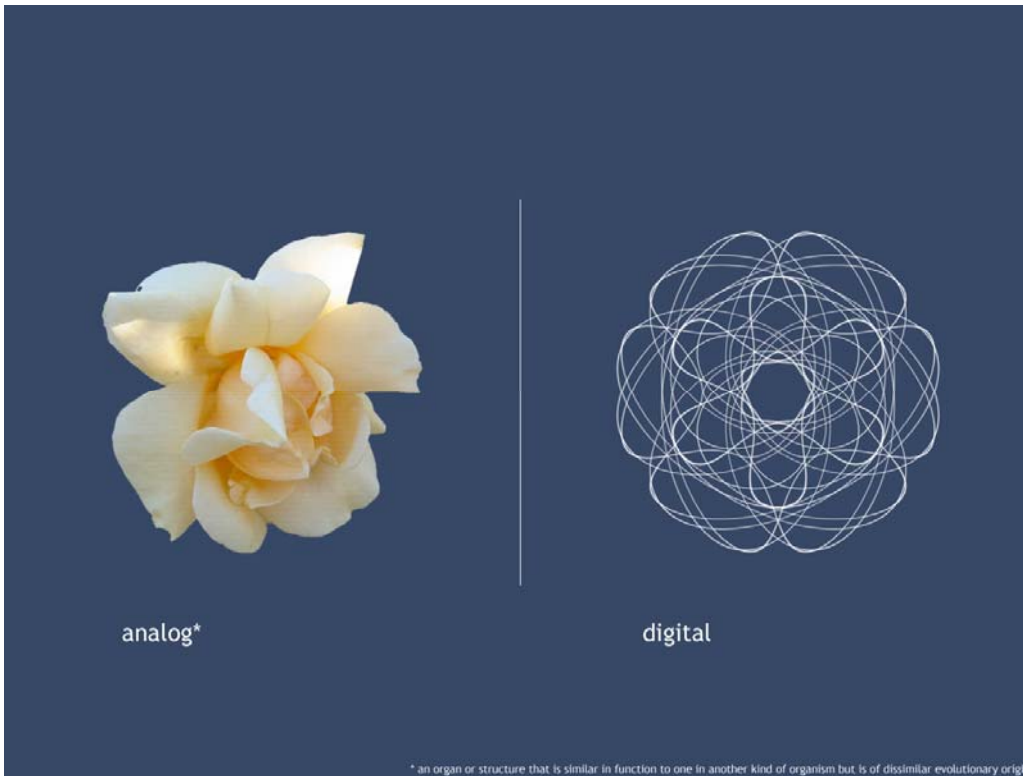
Capacity building

Secure funding

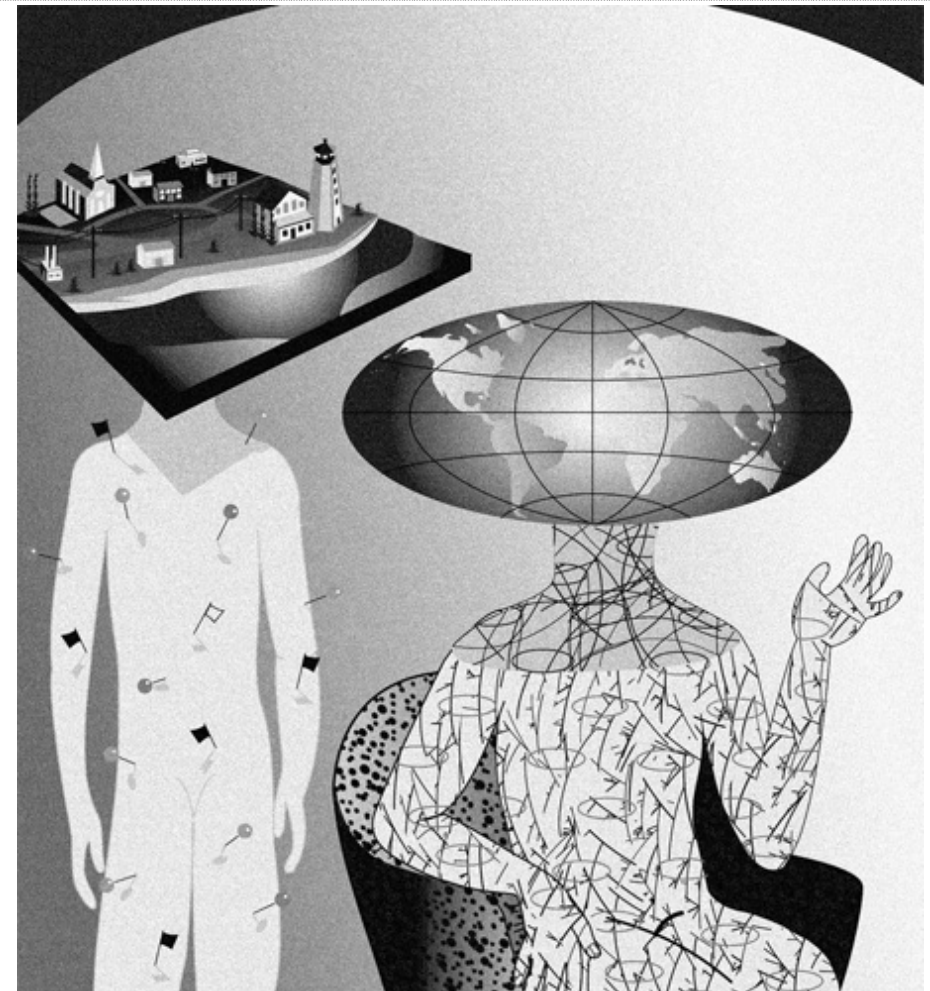
Thank you!

The World Is Going Digital and Global

Do People Remain Analogue and Local?



* an organ or structure that is similar in function to one in another kind of organism but is of dissimilar evolutionary origin





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Information Density vs. Life Expectancy

The Irony of Modern Media

