Next-generation soil systems for a sustainable future

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soil & landscape science lab

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Soil sustains life
ATMOSPHERE
respiration
evaporation
photosynthesis
precipitation
emissions
energy
flora & fauna
evaporation
BIOSPHERE
SOIL
HYDROSPHERE
element cycling
soil water
element uptake
runoff / seepage
leaching
soil formation
weathering
recharge
LITHOSPHERE

Soil is under threat

1/3 of world soils are moderately or severely degraded

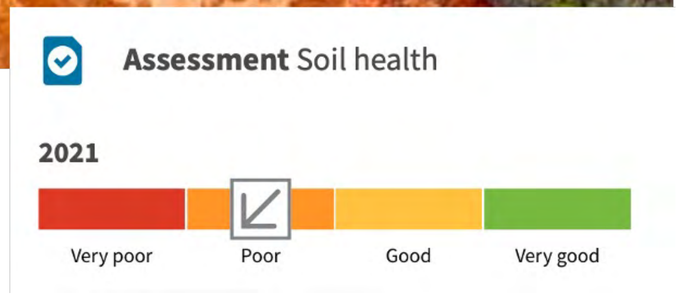
Desertification, erosion, acidification, salinization, nutrient imbalances, organic matter depletion, loss of biodiversity…

Without soil there is no life

…compounded by climate change, unsustainable land management, urbanization…

State of the environment Australia

But landscapes are degraded: erosion, acidification, soil carbon loss, salinisation, sodification, contamination…



Next-generation technologies in soil science

Key to helping us (scientists, land managers) to better understand soil ecosystems and address soil threats, climate change, and food insecurity.

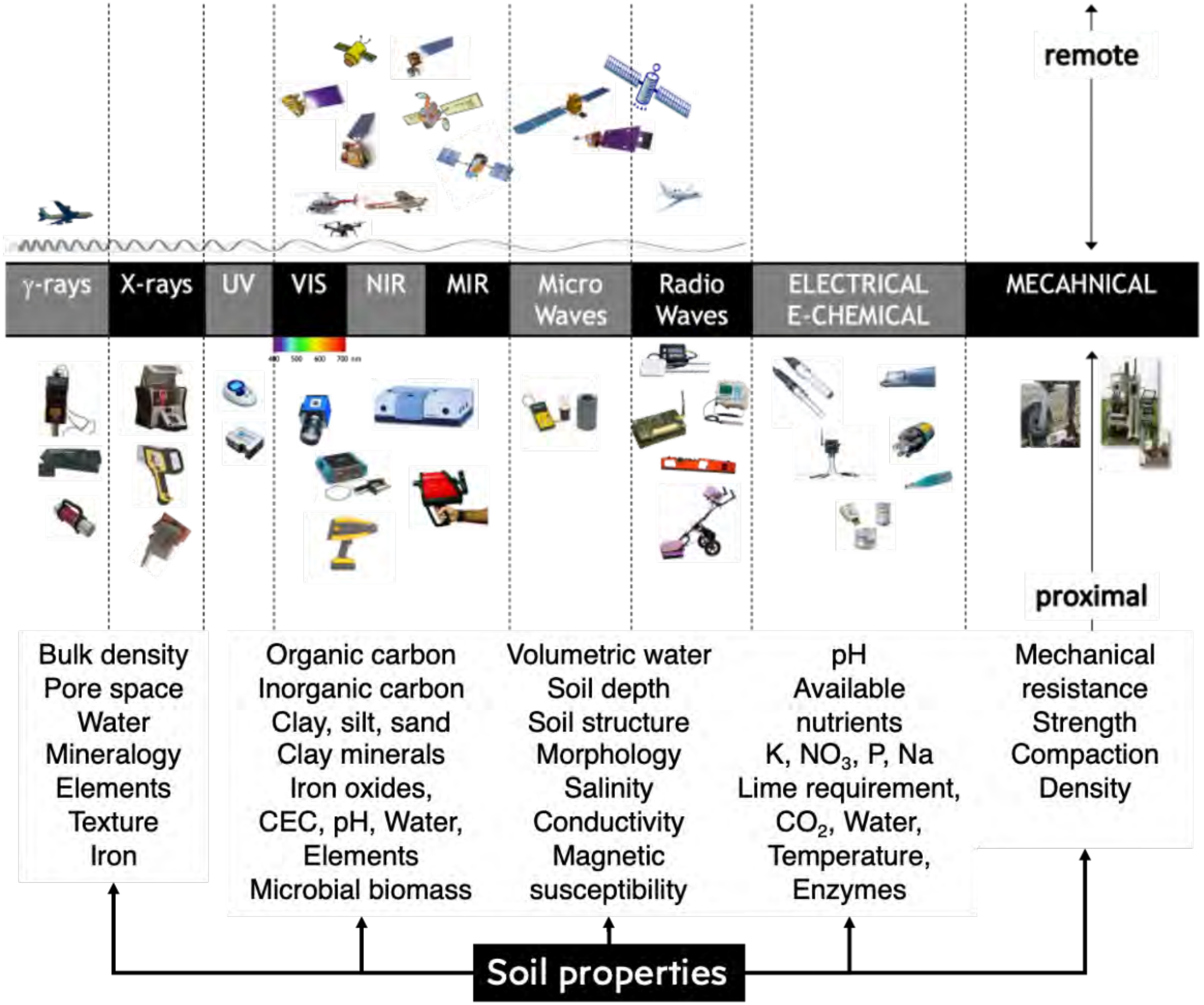
Outline:

1. **Briefly comment on some of these technologies**
2. **Will provide some examples of our research**
3. **Provide some final remarks**

[†] Methods and tools transforming conventional soil science by enhancing data collection, resolution, analysis, precision and understanding of soil processes, functions and dynamics.

Soil sensing

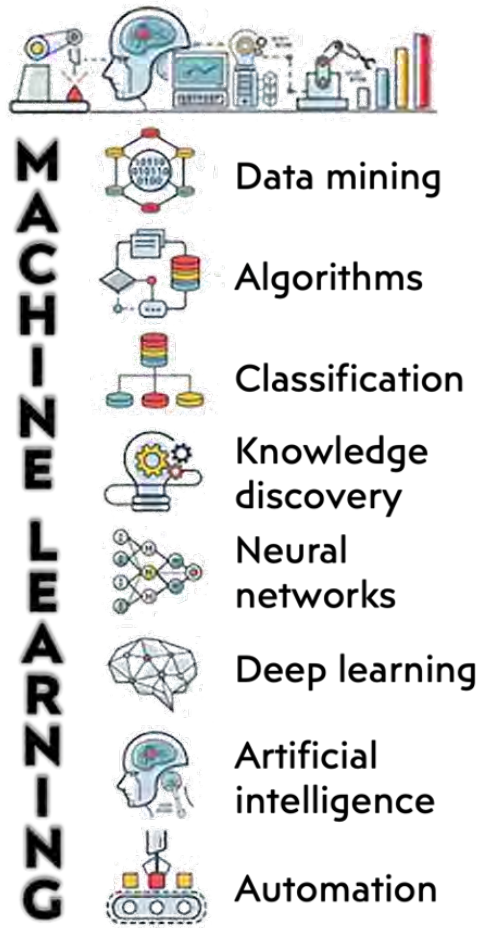
- Measurement is vital for understanding soil, agricultural productivity and environmental conservation.
- Sensing address many shortcomings of conventional soil measurement
- '..if we are to embrace soil health for sustainable development, then we'd better ensure that we know how to measure it.'
  Johan Bouma

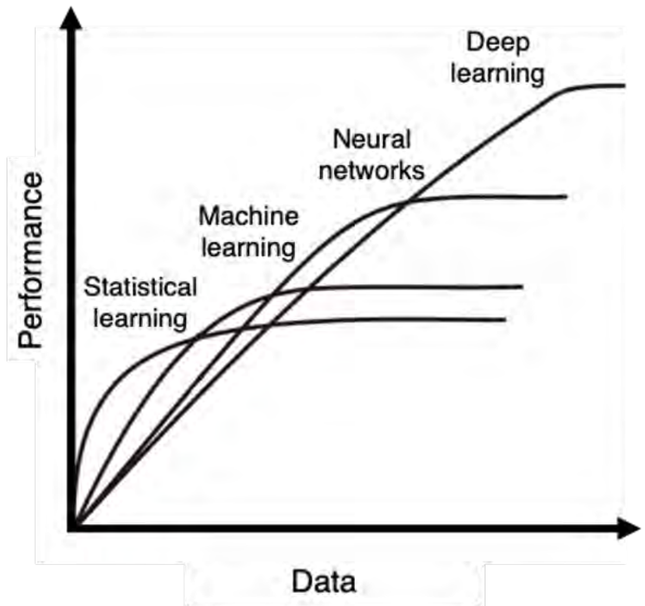


AI and machine learning in soil science

- ML offers a transformative opportunity for soil science, empowering us to unravel its complexities and to drive innovation

- By combining ML with scientific knowledge, we can develop innovative and practical solutions to protect our soils

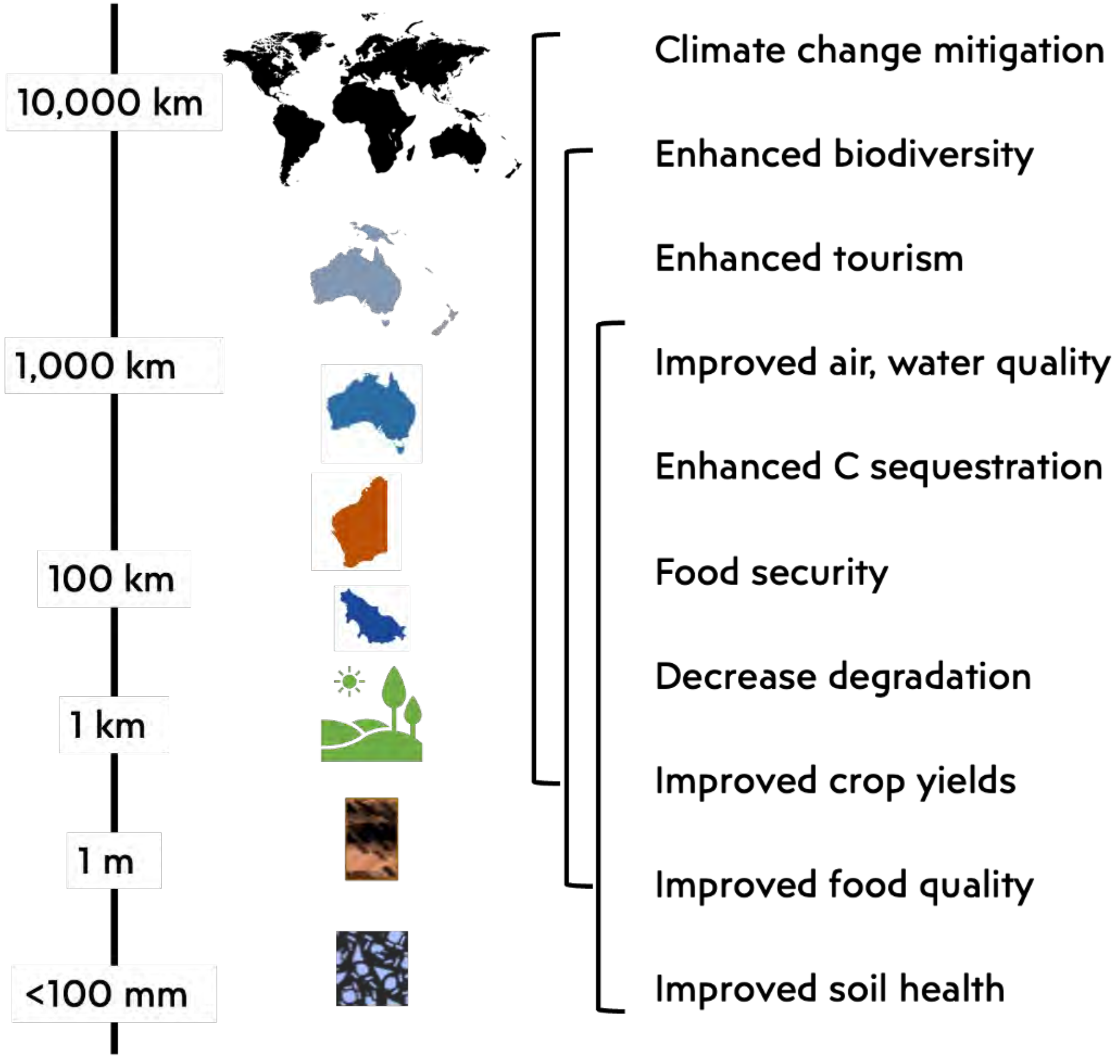




…we have not yet realized the full potential of AI and ML in soil science (---we need sensing!)

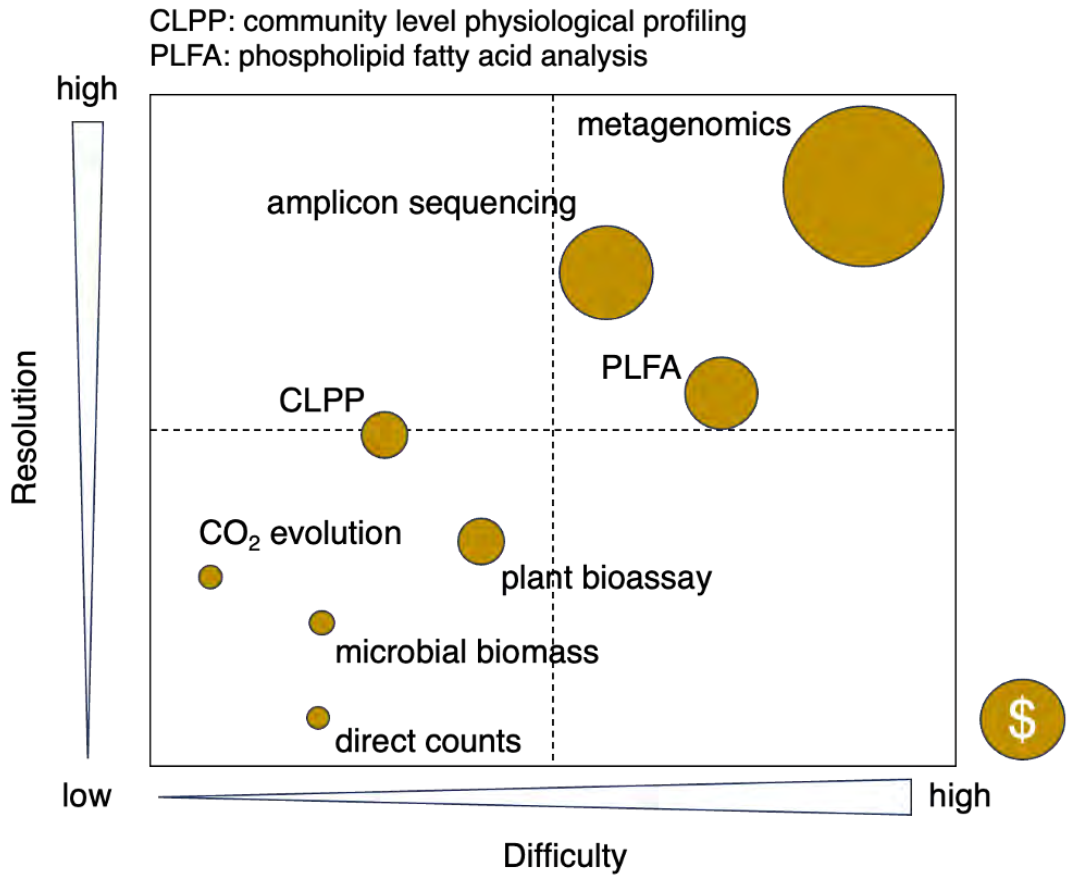
Multiscale understanding

- Multi-scale methods hold the key to unlocking a deeper understanding of soil processes and dynamics
- Need to bridge the gap between micro-scale interactions with plot/field scale and larger scale environmental impacts/practices.
- Though challenging this will allow us to create more effective solutions guiding both research and policy toward sustainable soil management



Microbial Genomics and Metagenomics

- Can provide unique insights into the soil microbiome, but they remain expensive and complex.
- We need to develop more cost-effective and practical microbial indicators that are more accessible for use in sustainable soil management practices.
- eDNA and spectroscopy-based approaches may provide more affordable and scalable methods to bridge the gap in understanding soil biology



Coleman & Jenkinson (1996); Wieder, et al. (2014); Abramoff et al. (2022)

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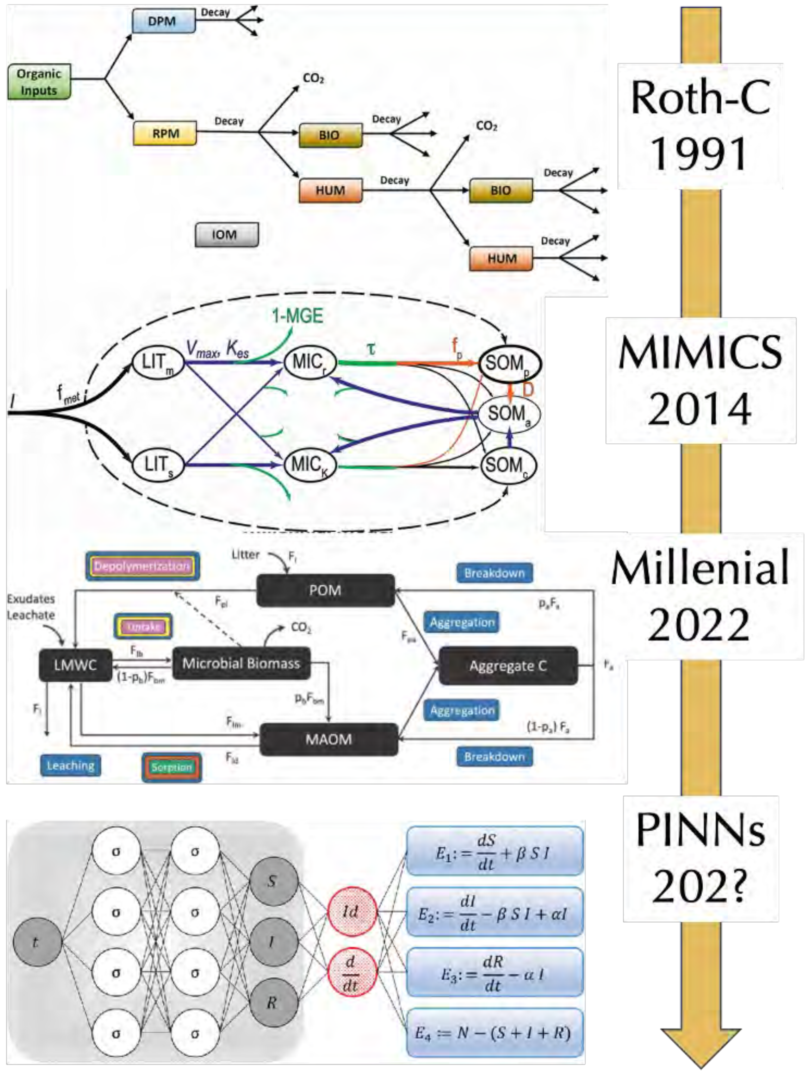
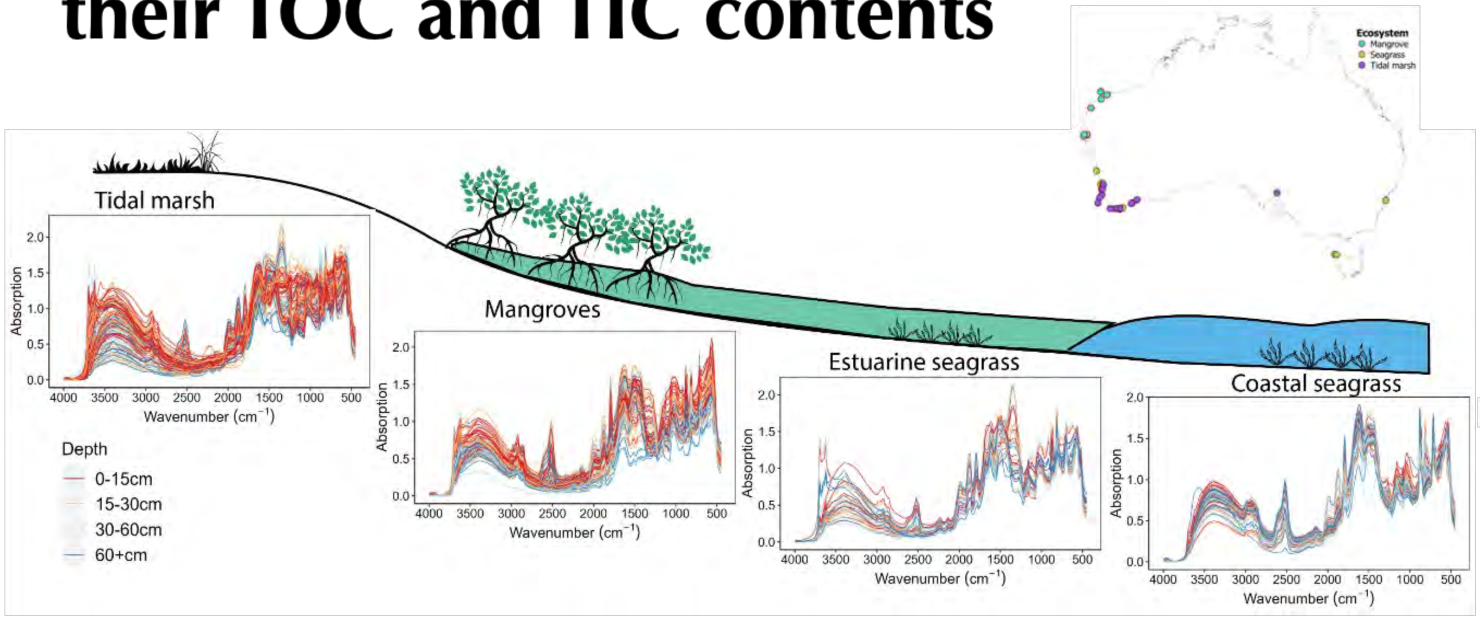
Process-based (carbon) models

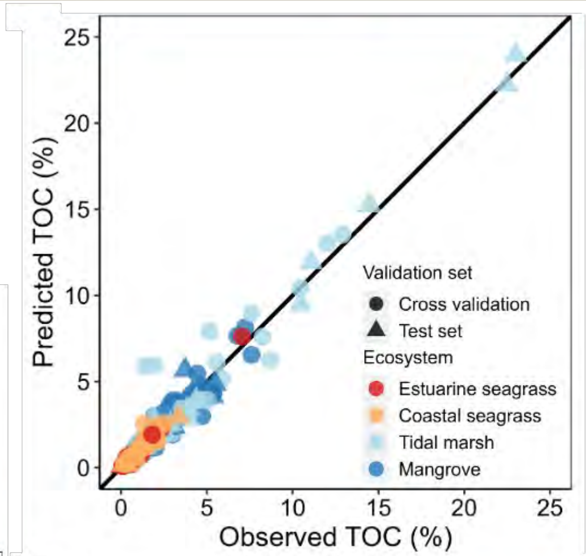
- New soil carbon models capture our current understanding of C dynamics, microbial decomposition, stabilization…
- Parameterization and validation challenges mean established models remain more reliable for now.
- Hybrid models, data assimilation and Physics-Informed Machine Learning (PIML/PINNs) will eventually replace purely mechanistic models, integrating empirical data with physical processes for better predictions.

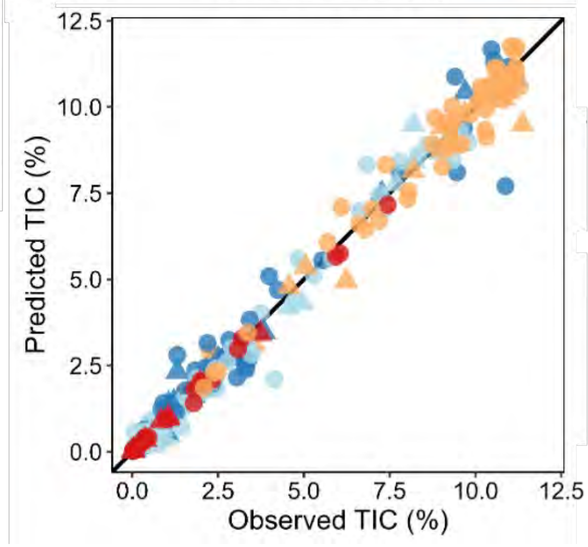


Some research

Provenance of blue carbon soils and their TOC and TIC contents

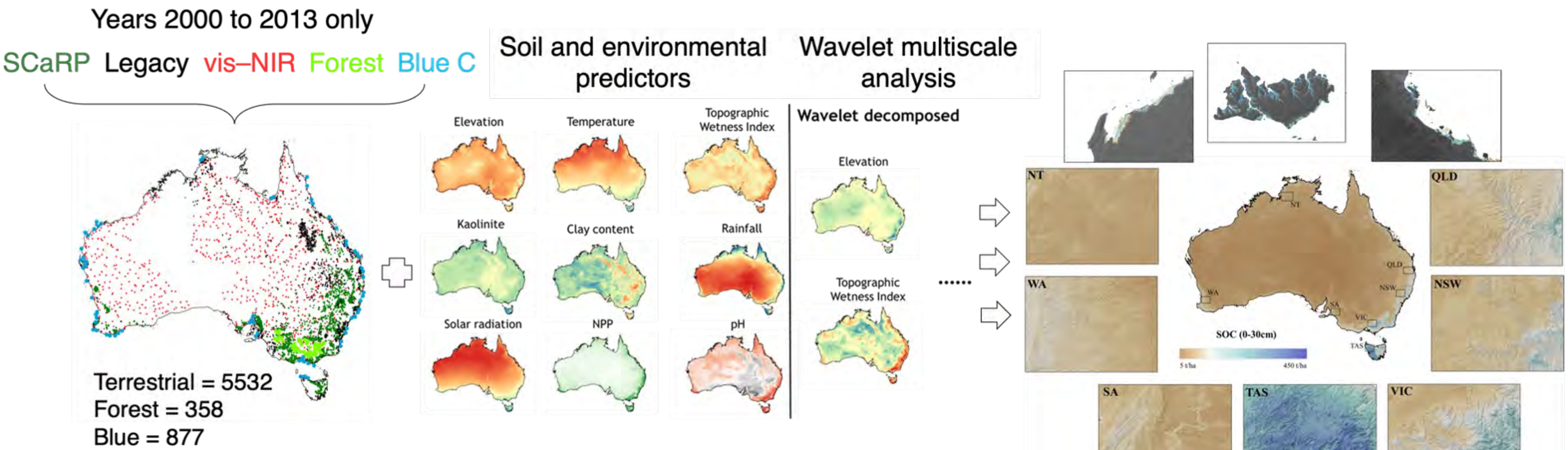






- Ecosystems have unique organic and mineral composition
- More freshwater inputs = increase clay + OC
- Less freshwater input = decreased clay, increase carbonates
- Could identify allochthonous vs autochthonous material

Multiscale terrestrial and coastal marine soil C stocks



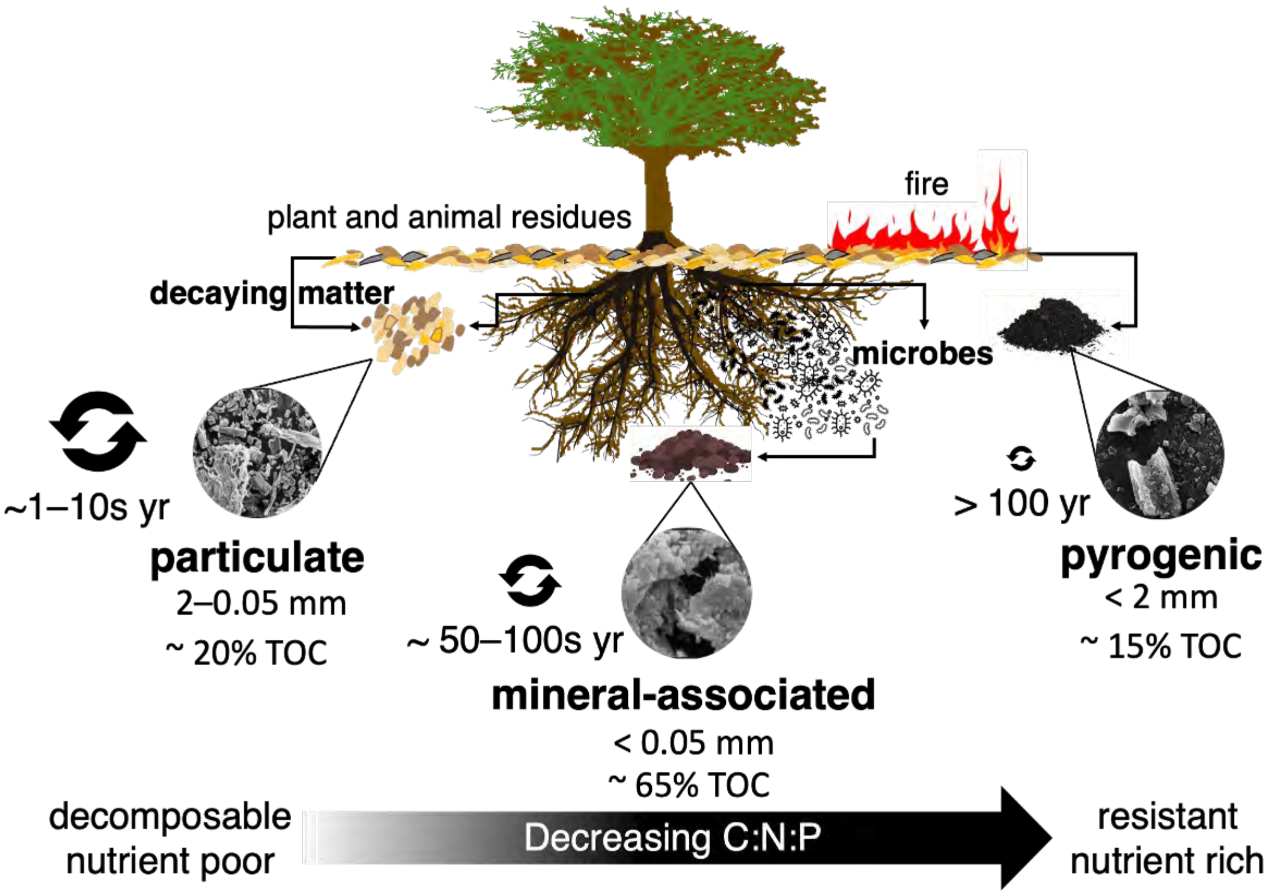
$S_C = f(S, Cl, O, R_{multiscale}, PM, Oceanographic) + \varepsilon$

Terrestrial mean: 36.2 t/ha (95% CI 25.7–51.3)
Blue mean: 61.8 t/ha (95% CI 35.4–108.8)

Terrestrial total: 27.9 Gt C (95% CI 19.8 - 39.6)
Blue total: 0.35 Gt C (95% CI 0.2 -- 0.6)

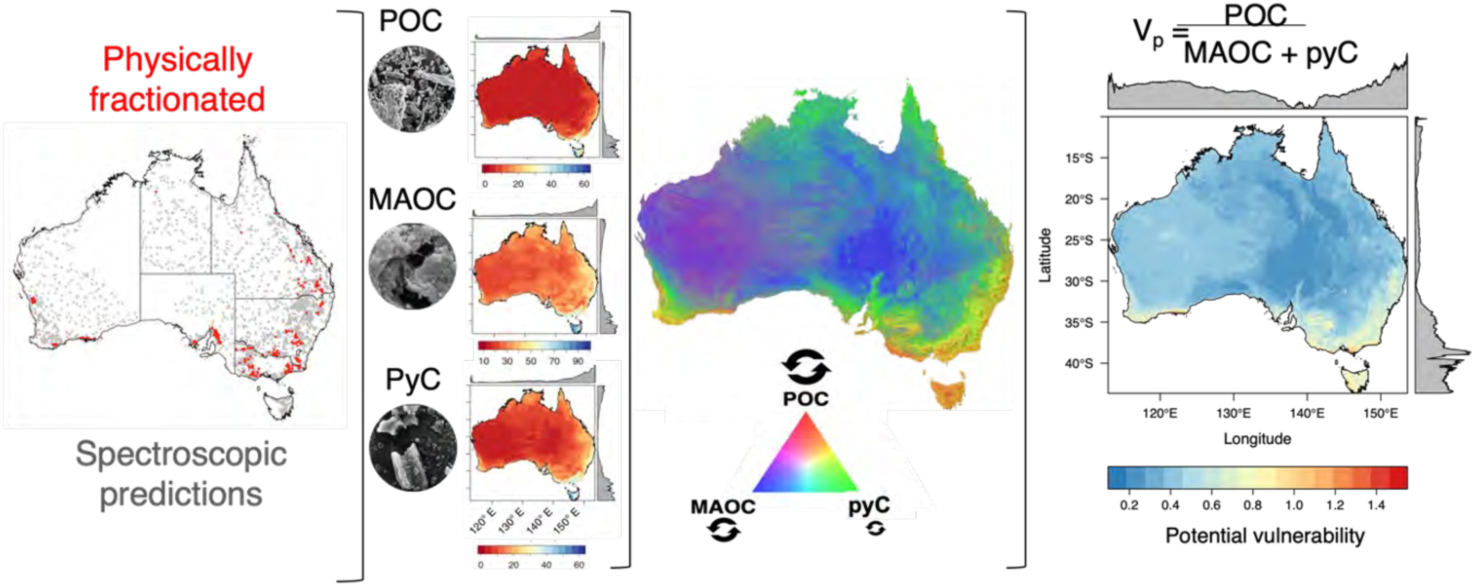
Soil organic carbon composition: the C fractions

- SOC composition simplified: three distinct fractions based on their physicochemical properties and turnover.
- Understanding POC, MAOC, and PyC is crucial for predicting carbon turnover, stabilisation, fertility, health.
- These fractions can guide practices to optimize C sequestration and ecosystem management.

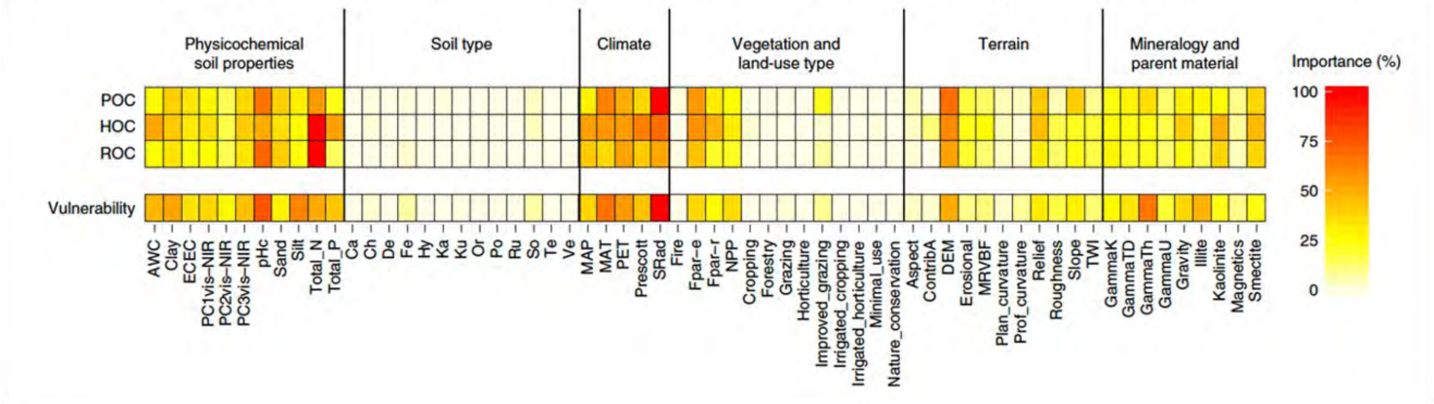


Multiscale controls and mapping of the C fractions & vulnerability

- helps understand C stability across Australia's diverse landscapes.
- informs management to improve C storage and monitoring.

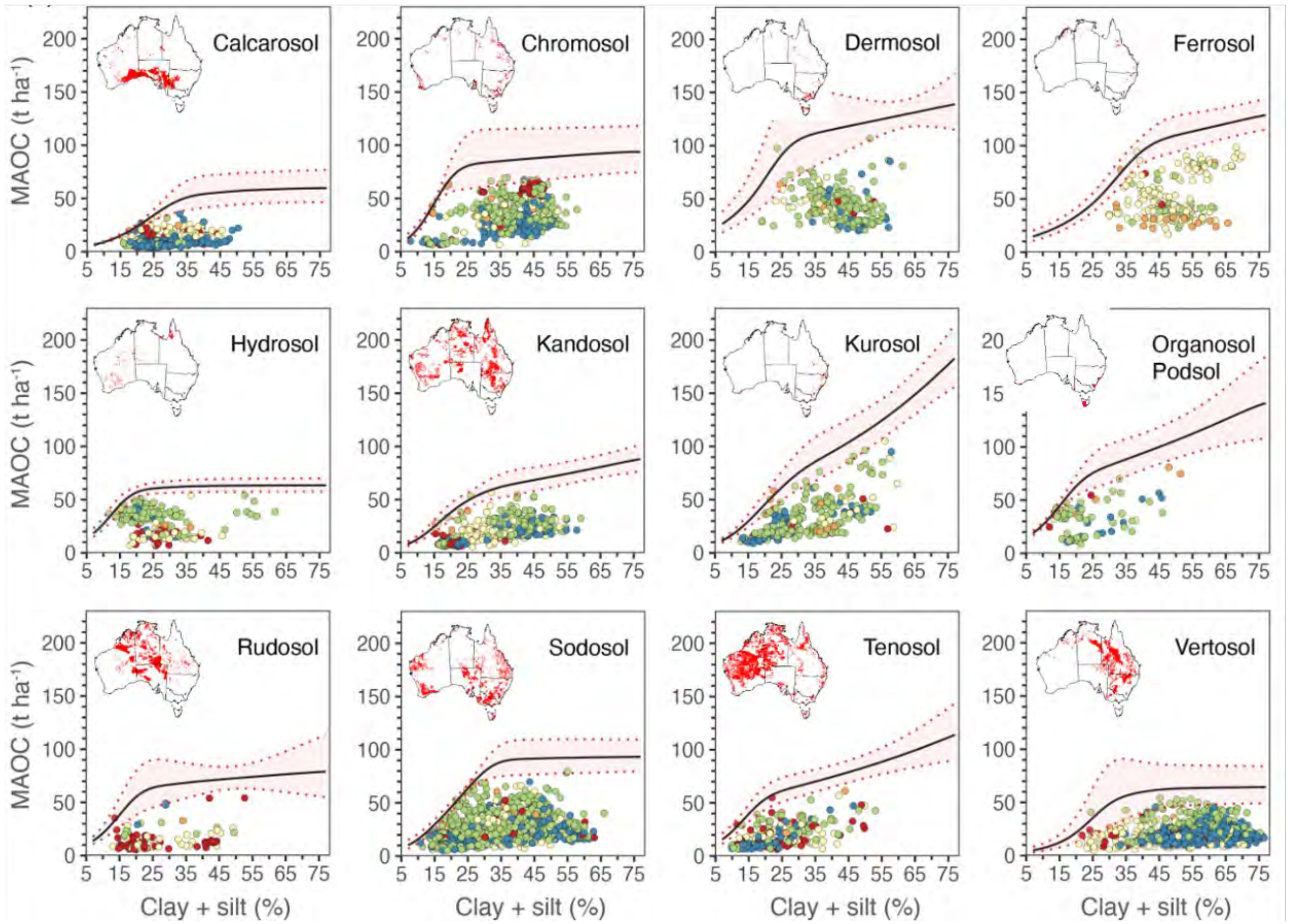


POC, MAOC, PyC and vulnerability in Australia modulated by regional environmental controls



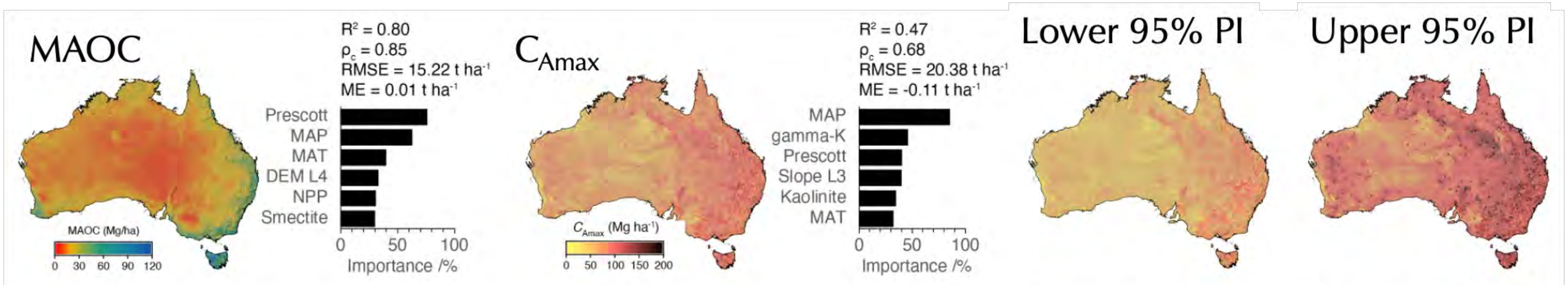
MAOC capacity and its deficit or sequestration potential

- Soil C has been depleted due to anthropogenic practices
- Soils can re-sequester C, but understanding their storage capacity is essential.
- C sequestration potential is determined by soil type and mineralogy, climate, and land management (pedoclimatic context)

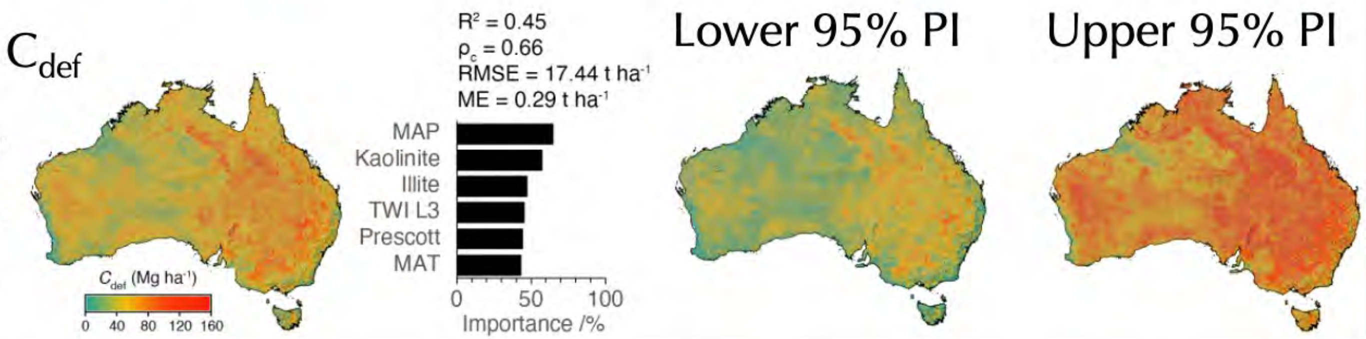


Maps of MAOC, C_{Amax}, C_{def} and their uncertainty

Digital mapping assimilated climate, vegetation, mineralogy and soil and landscape attributes) into the estimation of C_{Amax} and C_{def}



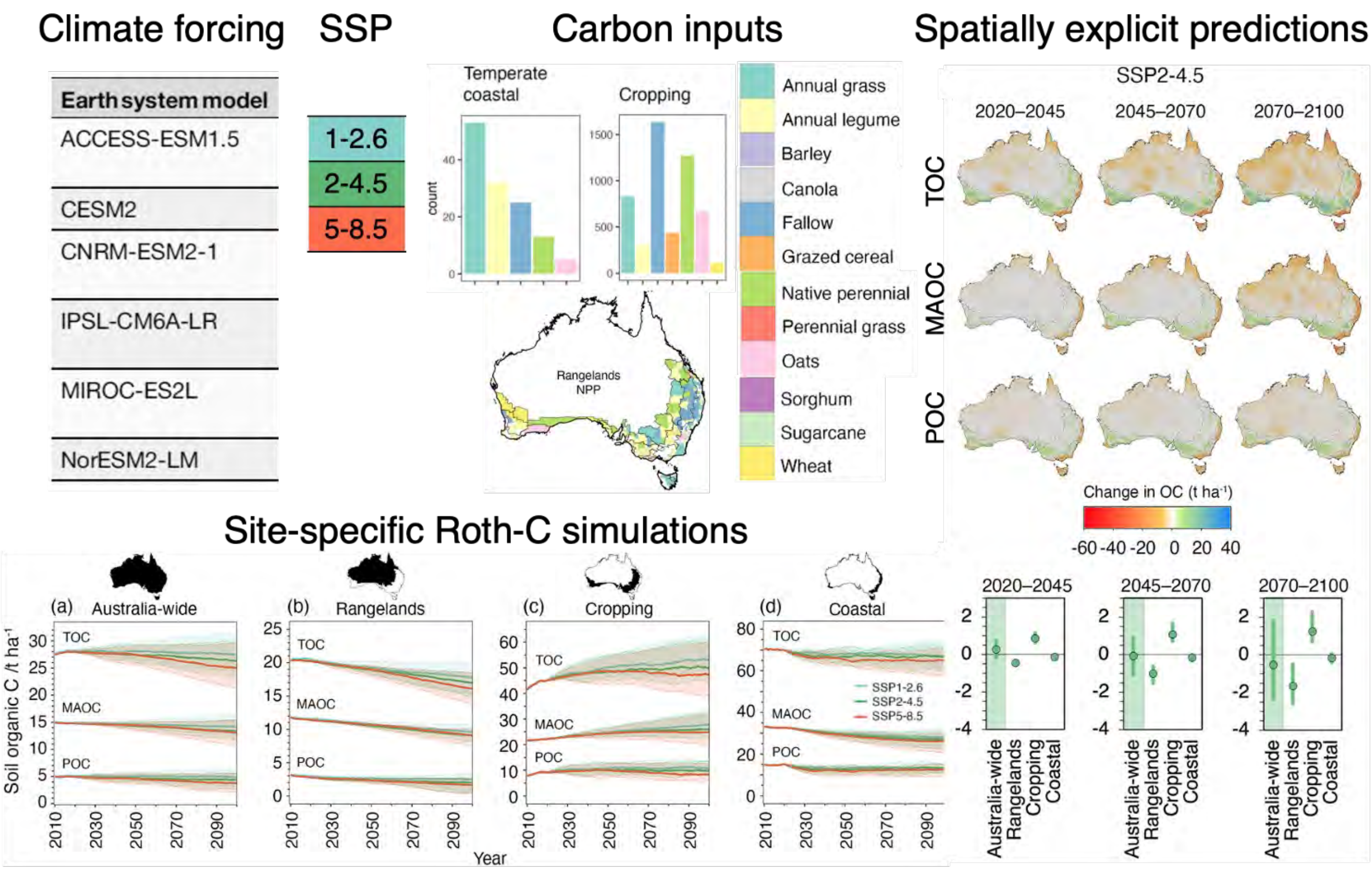
Australian soil has large potential, but limited largely by the pedoclimatic context and only to small degree by land management



Modelling Future Soil C change

- Australian soil is projected to be a net emitter of CO_2 due to warming, with losses accelerating under high-emission.

- The rangelands are most at risk.

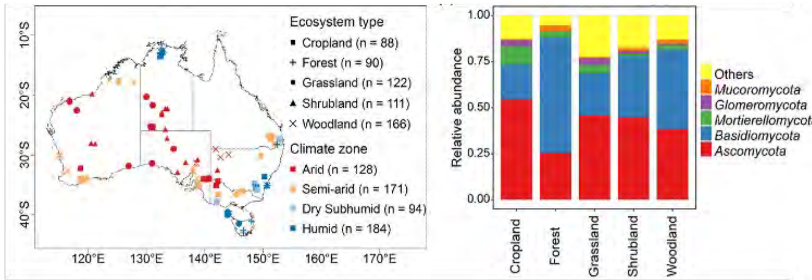


Understanding the soil microbiome

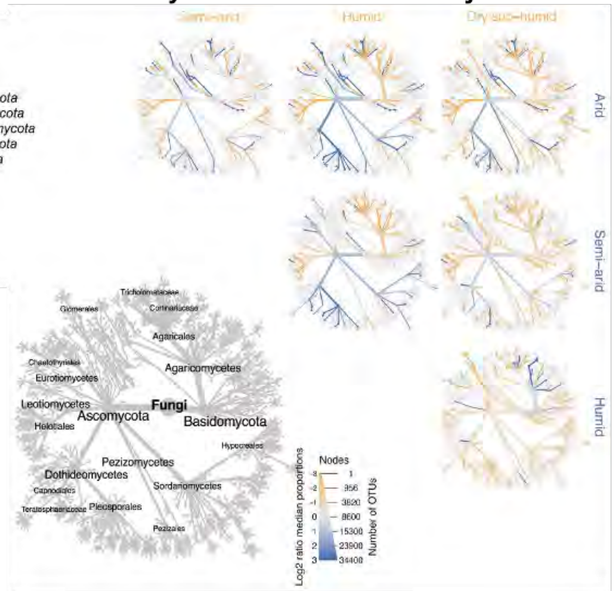
- Understanding the soil microbiome is crucial for assessing soil C, health, etc, and its role in ecosystem functioning.

- Improved measurement is needed – spectroscopic transfer function provide a (supplementary) solution.

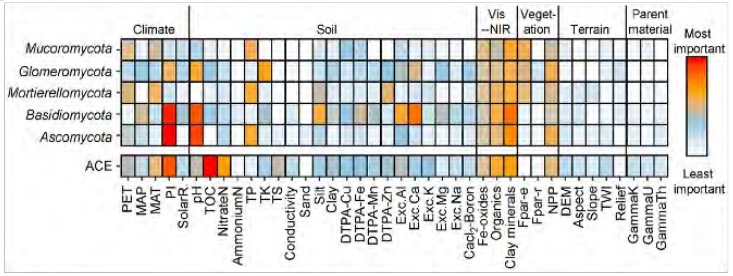
Sample locations and relative abundances of dominant soil fungal phylotypes in Australian ecosystem



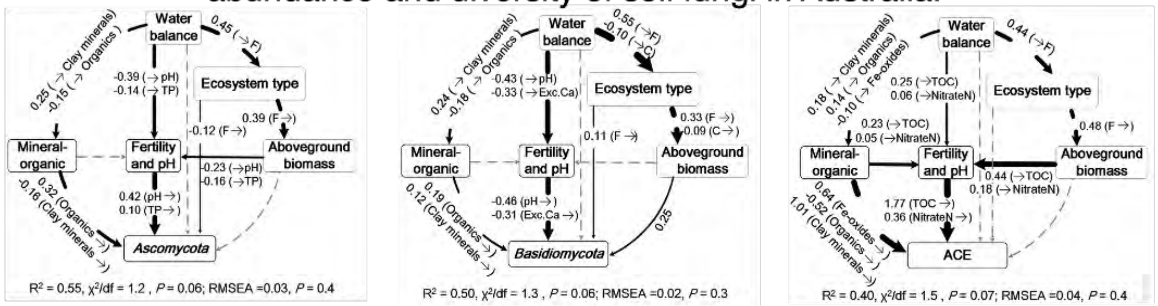
Taxonomic tree: Ascomycota and Basidiomycota



Important controls on the relative abundance of fungi



Ecosystem type, aridity, soil type, biomass, fertility and pH had significant effects on the abundance and diversity of soil fungi in Australia.



Final remarks and future directions

- Developing soil sensing technologies is crucial to meet data needs for tackling global challenges. (***Prioritize affordable, scalable multisensor systems***).

- Integrating machine learning with sensing and modelling is transforming soil science and will help to unlock new insights on soil functions and dynamics. (***Focus on multisensor fusion and on PIML to improve soil process models***).

- Comprehensive analysis of soil processes across (temporal and spatial) scales to deepen our understanding of soil systems and to guide solutions. (***New methods to link soil processes across scales.***)

- To fully realize the potential of soil biology, we need more affordable and efficient genomic tools to explore the soil microbiome in ecosystems. (***Innovate cheaper, efficient genomic technologies to explore microbial diversity and functions in soils***).

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Soil science must embrace innovative next-generation technologies to address our global environmental challenges. By collaborating across disciplines and developing innovative, cost-effective methods next-generation technologies, we can revolutionise our understanding of soil systems and drive sustainable solutions for the future.

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Thank you for your attention.