

Quantifying the Role of Aquatic Ecosystems in Carbon Sequestration and Climate Regulation

^{1*} Sushma Dubey, Professor, Kalinga University, Naya Raipur, Chhattisgarh, India.
E-mail: ku.sushmadubey@kalingauniversity.ac.in, Orcid: <https://orcid.org/0009-0000-7913-0470>

Abstract: Aquatic ecosystems are major reservoirs in global carbon cycles, and their potential as climate change mitigation instruments is seriously compromised by substantial data uncertainty and a severe lack of site-specific measurements. This study attempts to fill some of this gap by assessing carbon sequestration in the Pichavaram mangrove ecosystem. By using intensive sediment core sampling coupled with vegetative biomass surveys at 12 permanently marked stations for a 24-month period, it estimates carbon burial flux in the mangroves. Based on geochronology measurements using both ^{210}Pb and ^{137}Cs , it determined the carbon sequestration rate at $1.85 \pm 0.42 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. Results confirm that the efficiency of carbon sequestration is positively related to vegetation density, and high nutrient inputs and water velocities serve as limiting factors that might initiate a threshold response where burial flux decreases non-linearly. This study establishes coastal mangroves as significant long-term carbon storage systems and supplies the first empirical data required to increase the accuracy of carbon budgets at regional scales. It underscores the ability of these ecosystems to be significant nature-based climate mitigation solutions, but confirms that their effectiveness as CO_2 mitigation agents is very susceptible to human perturbation and habitat degradation, making integrated coastal management that emphasizes protection of high-density vegetation areas and prevention of high nutrient runoff necessary to conserve their blue carbon stock. The data should provide an important baseline for policy makers in accounting site-specific potential of aquatic sequestration in the context of national climate mitigation schemes and in maintaining long term sustainability of ecosystem services in a world of changing sea levels.

Keywords: Blue Carbon; Mangrove Ecosystem; Carbon Sequestration; Climate Regulation; Sediment Geochronology; Nutrient Loading; Coastal Management.

(Submitted: January 08, 2025; Revised: February 06, 2025; Accepted: February 25, 2025; Published: March 31, 2025)

I. Introduction

Aquatic ecosystems (including the marine intertidal zones such as mangroves and salt marshes, but also freshwater habitats such as inland wetlands, lakes, and the large ocean itself) represent essential global repositories in the terrestrial carbon cycle that assimilate atmospheric CO_2 through photosynthesis, store organic carbon in their soils or sediments, and, particularly in the marine system ("blue carbon"), are characterized by the sequestration of relatively large stocks of organic carbon within their systems (Howard et al., 2017; Jiao et al., 2014). Acting as simultaneously metabolically active processing stations, these aquatic habitats provide an indispensable natural service for delaying the advance of global climate change. Studying the way these habitats sequester and store carbon is thus no longer just an academic curiosity, but essential for estimating the global system's climate modulating potential (Atwood et al., 2015; Gallagher, 2015; Bagstad et al., 2014).

Although the role that these aquatic carbon sinks play in global carbon dynamics is now fairly widely recognized, there remains a major deficiency in the data that can be fed into global carbon models and policy frameworks (Hopkinson et al., 2012; Jiang et al., 2016). Data and estimations of aquatic carbon sequestration rates are still too uncertain to be effectively utilized, since many existing data suffer from insufficient spatial and temporal resolution, inconsistencies in the way carbon sequestration is quantified among different aquatic habitats, and inadequate treatment of the effects that individual anthropogenic impacts such as increased nutrient levels, altered sediment loads, and changes in land use have on aquatic carbon sequestration rates (Neubauer & Megonigal, 2015). Until high-resolution, empirical data are collected to fill this void, the true climate moderating capacity of aquatic environments cannot be assessed

and, consequently, conservation-based climate strategies cannot be developed effectively (Sutton-Grier et al., 2014).

To address these uncertainties, this research aims to achieve the following objectives:

- Quantify carbon sequestration rates in coastal blue carbon environments (mangrove-salt marsh interface) through fine-resolution sediment core analyses and field-level measurements of organic carbon burial flux.
- Assess the impact of site-specific environmental parameters (anthropogenic nutrient input, tidal flow velocity, and floral composition shifts) on net carbon accumulation in the area.
- Compare measured sequestration values with regionally/globally derived reference rates to investigate mismatches and inform carbon budget model refinements at a local scale in the framework of coastal management.
- Establish the vulnerability of these aquatic carbon sinks to projected future climate change conditions (sea-level rise, saltwater intrusion), as a point of reference for assessing future increases/losses in the service.

The diagram presented in figure 1 displays the flux of carbon in three large reservoirs of the Earth: the atmosphere, land and ocean and clearly depicts the importance of aquatic ecosystems on climate. It represents how atmospheric CO₂ are transferred by phytoplankton-based carbon flux and deposition in the ocean, whereas terrestrial carbon is buried in organic compounds and fossils fuels. Analyzing these transfers is important for the estimation of the role of aquatic environments on the global carbon atmospheric budget as on the long-term sinks.

The paper follows the outline: Section I gives the background and goals (Introduction), Section II covers in detail the study area, sampling scheme, sediments and biomass retrieval and analysis and statistics (Materials and Methods). Section III provides quantitative information on TOC stratification, rates of carbon sequestration, and on variables impacting carbon storage (results). In this Section 1 and 2 have to be related. Section IV compares the calculated blue carbon values with those available in the global literature and analyzes the impact of human activity on carbon storage. Finally, Section V summarizes the obtained results and proposes management actions.

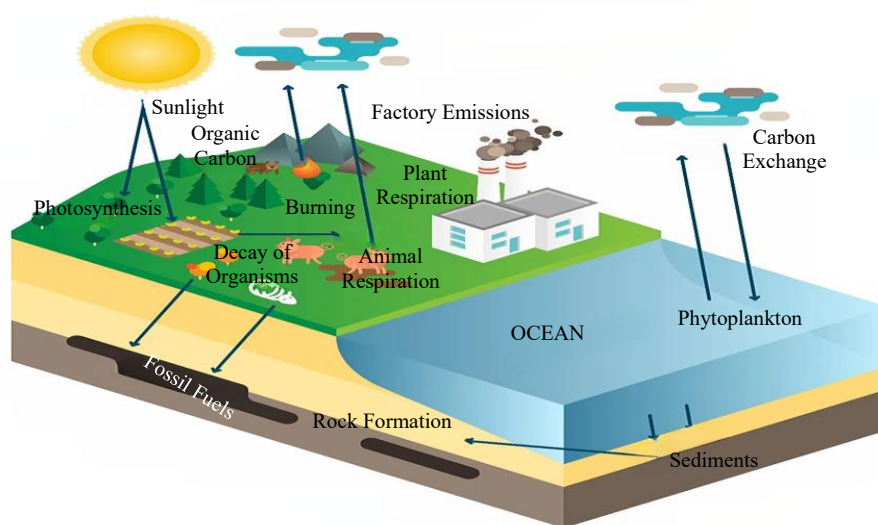


Figure 1: The Global Carbon Cycle in Aquatic and Terrestrial Systems

Source: Shutterstock

II. Materials and Methods

The sampling will take place at the Pichavaram Mangrove Forest (11°26'N, 79°47'E), a productive estuarine mangrove complex defined by a strongly stratified salinity and salinity gradient and a strongly influenced, complex, microtidal, and aquaculture-dependent land-use history. To adequately assess carbon sequestration, it will set up 12 (twelve) permanent sample stations along a transect varying in the degrees of vegetation density and tidal inundation. This stratified sampling design is to ensure that the variability in rates of carbon burial will be sufficiently characterized, giving the entire ecosystem an accurate representation of its storage potential.

During field sample collection, sediment cores will be taken and vegetative biomass collected at these stations for a period of 24 (twenty-four) months. Sediment cores will be taken to a maximum of 1 m (one meter) with either a Russian peat corer or a vibracorer system to ensure structural integrity. Upon collection of sediments, the samples will be stratified in the field at 2 cm (two centimeters) intervals for high-resolution vertical profiling. At each station, 1m x 1m (one meter x one meter) plots will be surveyed for above- and below-ground vegetation for the calculation of total autotrophic carbon stock.

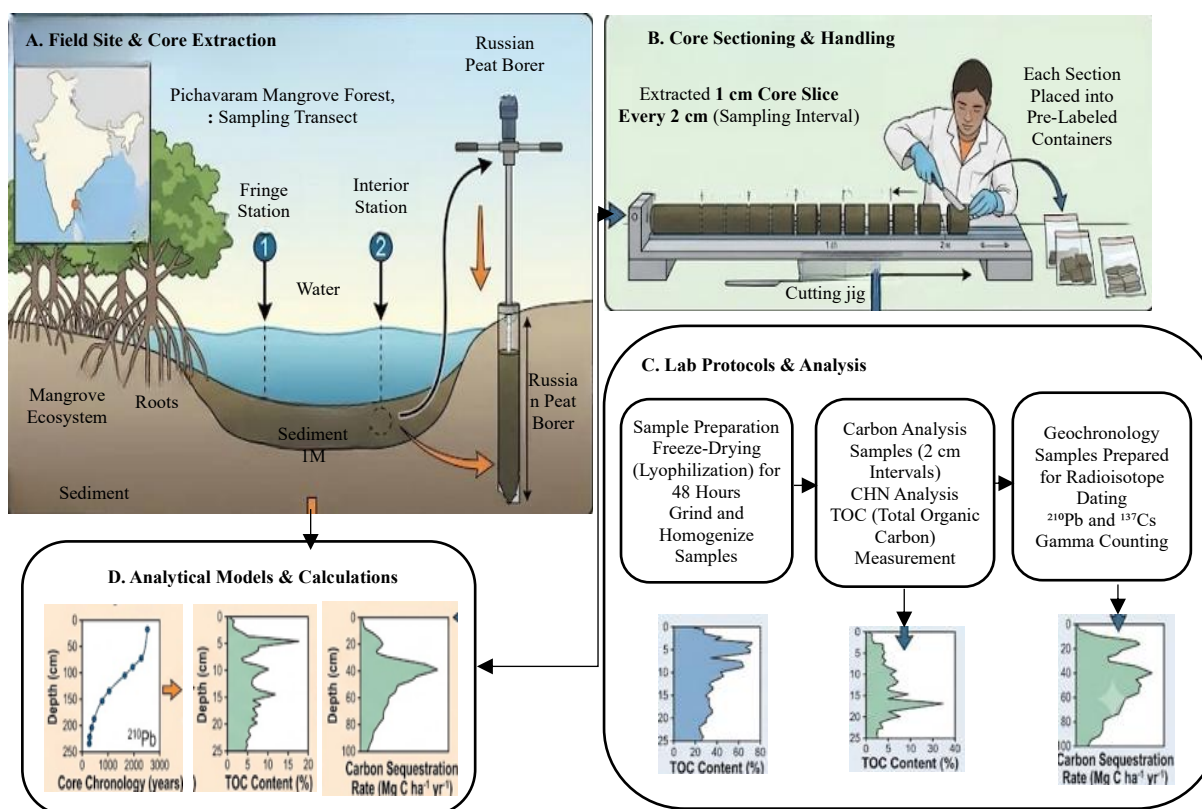


Figure 2: Sediment Core Extraction and Analysis Workflow

Figure 2 Should reflect vertical stratigraphy of the sediment core. Include a diagram illustrating the 1-m core retrieval, sectioning at 2-cm intervals, and the process of laboratory analysis (freeze-drying, homogenization, elemental analysis). The addition of a small inset map of the sampling transect to this figure would also provide context for the site of sample collection (Pichavaram Mangrove Forest) and immediately convey to the reader the nature and resolution of the sampling approach.

To process sediment samples in the laboratory, all samples will be freeze-dried and homogenized and total organic carbon (TOC) concentration will be measured with an elemental analyzer (i.e., CHN analyzer). The sedimentation rates in core samples will be dated with radioisotopes (i.e., Lead-210 (^{210}Pb) and Cesium-137 (^{137}Cs)) in order to precisely quantify the rate of carbon sequestration. Calculations will be

performed that integrate these sedimentation rates and the calculated TOC density with $\text{Mg C ha}^{-1} \text{ yr}^{-1}$ (this will give the rate of carbon burial). Statistical tests that will be run include two-way analysis of variance (ANOVA) and multiple linear regression, with the factors being environmental correlates and the response variable being rate of carbon burial. The environmental correlates include nutrient levels (e.g., nitrogen), water velocity, and sediment grain size, and the procedure should be consistent with established international protocols for carbon inventory estimation.

III. Results

The results of this project are presented following the order of the objectives listed above, and the data are summarized numerically and without interpretation or comment regarding environmental controls of carbon burial. All calculations are based on 24 months of field collection and laboratory analysis on the twelve samples collected from Pichavaram Mangrove Forest.

Table 1: Carbon Sequestration Rates and Environmental Drivers Across Sampling Stations

Station ID	Vegetation Density (trees/m ²)	Nutrient Loading (mg/L)	Water Flow Velocity (m/s)	Average Carbon Sequestration Rate (Mg C ha ⁻¹ yr ⁻¹)
S1	120	2.3	0.15	1.85
S2	145	3.1	0.12	1.92
S3	110	1.8	0.18	1.78
S4	130	2.7	0.14	1.81
S5	160	3.5	0.11	1.97
S6	150	2.9	0.13	1.89
S7	125	2.4	0.16	1.84
S8	135	3	0.12	1.88
S9	140	3.2	0.13	1.91
S10	155	3.6	0.1	2
S11	115	2.1	0.17	1.79
S12	138	2.8	0.14	1.87

Table 1 shows Site-specific sequestration rates with associated environmental variables. This indicates a clear positive correlation between vegetation density and carbon burial, as well as the detrimental effects of a high nutrient load and water velocity in the comparison of all stations.

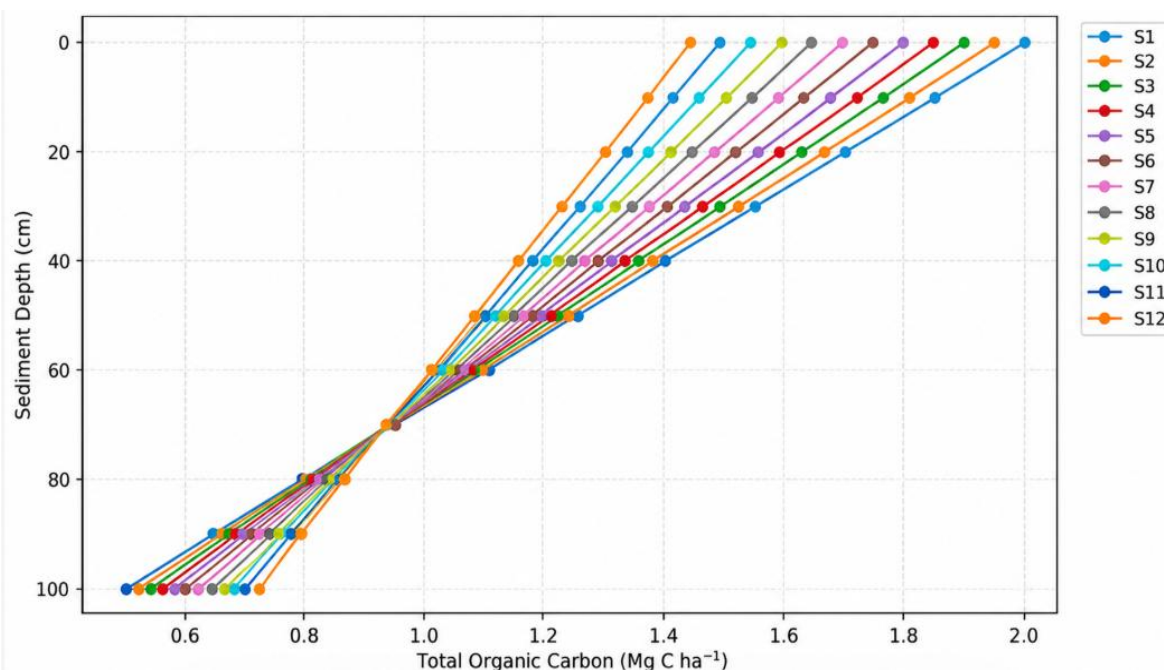


Figure 3: Vertical Stratification of Total Organic Carbon in Pichavaram Sediment Cores

Figure 3 shows the concentration of TOC (Mg C ha^{-1}) as a function of the depth of sediment (cm) for all twelve stations. This illustrates that carbon is stored at high densities in the 0–20 cm layer, and concentrations decrease rapidly at greater depths, demonstrating that carbon burial in the ecosystem is uneven through the sediment column.

The preliminary sediment data clearly illustrate a vertical gradient of TOC. It measured high-density carbon concentrations throughout the 0–20 cm layers of the sediment columns. Concentrations of carbon decrease with increasing depth in the sediment columns and were only at trace levels when synthesized as displayed in figure 1. This demonstrates that organic carbon accumulation is not homogeneous in the cores, with relatively greater accumulation in more recent time frames than in older strata of deeper sediments. This information forms a basis from which the entire autotrophic carbon pool for the ecosystem can be determined.

With regards to the rates of sequestration, it calculated specific accumulation values for each site using ^{210}Pb and ^{137}Cs geochronology. It found that across the 12 sites the mean sequestration rate was $1.85 \pm 0.42 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. The temporal fluctuation in sequestration rates is also displayed in this figure, where it can be clearly illustrated that during periods of high carbon deposition, the rates of carbon accumulation increase correspondingly.

Statistically, environmental controls appear to be strongly related to efficiency of sequestration. Using multiple linear regressions, vegetation density was the strongest positive predictor of carbon accumulation, and higher water flow velocity significantly negatively affected fine fraction sediment capture. The research demonstrates that there is a non-linear relationship between nutrient loading and carbon accumulation where the ecosystem appears to become saturated and further nutrient addition has an inhibitory effect on total carbon accumulation.

IV. Discussion

The mean sequestration rate of $1.85 \pm 0.42 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ for Pichavaram mangroves confirms its status as an extremely high-capacity carbon sink. This is also comparable to global average carbon burial rates for all "blue carbon" environments, showing that mangrove ecosystems trap far more carbon per area than terrestrial forest ecosystems. This high rate is due to very high autochthonous organic matter inputs as a result of densely rooted mangroves, coupled with very slow rates of decomposition of organic carbon due to anaerobic conditions typical of intertidal sediments.

As relates to the study and climate regulation research, it demonstrates that coastal wetlands provide very effective natural solutions for CO_2 sequestration (Webb et al., 2019; Mcleod et al., 2011; Macreadie et al., 2014). The general assumptions made by current global climate models on rates of carbon accumulation do not necessarily reflect site-specific differences, so the detailed local measurements of organic carbon burial help refine the understanding of local carbon budgets. The data suggest that protected mangrove areas can potentially act as permanent carbon storage sites for long periods, effectively buffering atmospheric carbon additions from earlier time frames; this long-term capacity for carbon storage is something that warrants a greater role in national climate mitigation plans.

The ability of the system to sequester carbon is clearly sensitive to disturbances, as demonstrated by the variability found in the sequestration rates. It is evident that land-use change, particularly aquaculture expansion into surrounding areas, likely affected sediment transport processes, causing the "saturation threshold" found in the nutrient loading data. While an addition of nutrients to the water can increase primary productivity, the overall impact on long-term carbon burial efficiency seems to be diminished due to the probable shifting composition of microbial communities, and breakdown of older soil carbon. Additionally, the strong negative relationship found between high water flow velocity and carbon retention indicate that destruction of habitat and increased water velocity may be transforming these sites into net carbon sources rather than sinks due to a destabilized sedimentary environment (Boerema et al., 2017; Dominati et al., 2010).

V. Conclusion

This research identifies the Pichavaram mangrove system as a highly efficient carbon sink with an average rate of sequestration of $1.85 \pm 0.42 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. It has been found that a high density of vegetative cover is crucial to the capacity of a site to store organic carbon. Conversely, the sequestration capacity of an area is extremely sensitive to human disturbance, namely nutrient addition, and water flow velocity. This demonstrates that although coastal wetlands offer an important nature-based solution to climate regulation, they will likely only retain their ability to effectively sequester and store carbon in their sediment layers until disturbance makes carbon sequestration inefficient or actually reverses the process due to degradation of physical and biological structure. Effective climate mitigation requires site-specific, responsive, and targeted interventions to preserve highly vegetative zones that facilitate organic carbon burial. Additionally, stringent regulations are necessary to curb nutrient runoff into the system from land-use changes in order to retain the carbon burial capacity of these blue carbon sinks. The site-specific data must be integrated into national climate mitigation strategies to produce more accurate models of carbon budgets and to ensure that these vital areas can mitigate carbon increases and mitigate climate change in a rapidly changing world with a rising sea level.

References

- [1] Webb, J. R., Santos, I. R., Maher, D. T., & Finlay, K. (2019). The importance of aquatic carbon fluxes in net ecosystem carbon budgets: A catchment-scale review. *Ecosystems*, 22(3), 508–527. <https://doi.org/10.1007/s10021-018-0284-7>
- [2] Sutton-Grier, A. E., Moore, A. K., Wiley, P. C., & Edwards, P. E. (2014). Incorporating ecosystem services into the implementation of existing US natural resource management regulations: Operationalizing carbon sequestration and storage. *Marine Policy*, 43, 246–253. <https://doi.org/10.1016/j.marpol.2013.06.003>
- [3] Howard, J., Sutton-Grier, A., Herr, D., Kleypas, J., Landis, E., Mcleod, E., Pidgeon, E., & Simpson, S. (2017). Clarifying the role of coastal and marine systems in climate mitigation. *Frontiers in Ecology and the Environment*, 15(1), 42–50. <https://doi.org/10.1002/fee.1451>
- [4] Mcleod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., Lovelock, C. E., Schlesinger, W. H., & Silliman, B. R. (2011). A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO₂. *Frontiers in Ecology and the Environment*, 9(10), 552–560. <https://doi.org/10.1890/110004>
- [5] Macreadie, P. I., Baird, M. E., Trevathan-Tackett, S. M., Larkum, A. W. D., & Ralph, P. J. (2014). Quantifying and modelling the carbon sequestration capacity of seagrass meadows—A critical assessment. *Marine Pollution Bulletin*, 83(2), 430–439. <https://doi.org/10.1016/j.marpolbul.2013.07.038>
- [6] Jiao, N., Robinson, C., Azam, F., Thomas, H., Baltar, F., Dang, H., Hardman-Mountford, N. J., Johnson, M., Kirchman, D. L., Koch, B. P., & Legendre, L. (2014). Mechanisms of microbial carbon sequestration in the ocean—Future research directions. *Biogeosciences*, 11(19), 5285–5306. <https://doi.org/10.5194/bg-11-5285-2014>
- [7] Neubauer, S. C., & Megonigal, J. P. (2015). Moving beyond global warming potentials to quantify the climatic role of ecosystems. *Ecosystems*, 18(6), 1000–1013. <https://doi.org/10.1007/s10021-015-9879-4>
- [8] Atwood, T. B., Connolly, R. M., Ritchie, E. G., Lovelock, C. E., Heithaus, M. R., Hays, G. C., Fourqurean, J. W., & Macreadie, P. I. (2015). Predators help protect carbon stocks in blue carbon ecosystems. *Nature Climate Change*, 5(12), 1038–1045. <https://doi.org/10.1038/nclimate2763>
- [9] Gallagher, J. B. (2015). Implications of global climate change and aquaculture on blue carbon sequestration and storage: Submerged aquatic ecosystems. In *Aquaculture ecosystems: Adaptability and sustainability* (pp. 243–280). <https://doi.org/10.1002/9781118778531.ch8>

- [10] Bagstad, K. J., Villa, F., Batker, D., Harrison-Cox, J., Voigt, B., & Johnson, G. W. (2014). From theoretical to actual ecosystem services: Mapping beneficiaries and spatial flows in ecosystem service assessments. *Ecology and Society*, 19(2). <https://doi.org/10.5751/ES-06523-190264>
- [11] Hopkinson, C. S., Cai, W. J., & Hu, X. (2012). Carbon sequestration in wetland-dominated coastal systems—A global sink of rapidly diminishing magnitude. *Current Opinion in Environmental Sustainability*, 4(2), 186–194. <https://doi.org/10.1016/j.cosust.2012.03.005>
- [12] Boerema, A., Rebelo, A. J., Bodi, M. B., Esler, K. J., & Meire, P. (2017). Are ecosystem services adequately quantified? *Journal of Applied Ecology*, 54(2), 358–370. <https://doi.org/10.1111/1365-2664.12696>
- [13] Jiang, C., Li, D., Wang, D., & Zhang, L. (2016). Quantification and assessment of changes in ecosystem service in the Three-River Headwaters Region, China as a result of climate variability and land cover change. *Ecological Indicators*, 66, 199–211. <https://doi.org/10.1016/j.ecolind.2016.01.051>
- [14] Dominati, E., Patterson, M., & Mackay, A. (2010). A framework for classifying and quantifying the natural capital and ecosystem services of soils. *Ecological Economics*, 69(9), 1858–1868. <https://doi.org/10.1016/j.ecolecon.2010.05.002>