Synergistic Effects of Cover Cropping, Intercropping, and No-Tillage Systems On Soil Quality and Optimal Crop Recommendations Across Ecological Zone in the Global South

Akshat Sungkur
SBE - Business Analytics
University of Maastricht

June 28, 2025

Abstract

Farmers in the Global South face chronically degraded soils and low crop yields, posing a major threat, particularly in agriculture-dependent, climate-vulnerable, and natural hazard-prone countries. While individual sustainable practices - cover-cropping, intercropping, and no-tillage systemseach offer well-documented benefits, their combined benefits are overlooked. In this thesis, a data-driven selection of crops is selected for further analysis. A multi-criteria framework is deployed to identify the most promising crop species. The criteria were cover-crop suitability (%), intercrop suitability (%), no-tillage suitability (%), hardiness, water needs, allelopathy, temperature needs, soil management needs, and machinery needs. Those scores are then aggregated into an overall suitability index, and the robustness of the results is tested through a Monte Carlo-style perturbation of the weights. 10,000 perturbations of random weights of $\pm 50\%$ which is more than enough to cross out uncertainties or bias. Next and final step, best-fitting crops for each ecological zone in the Global South are matched and final recommendations are made. All that, focusing on our goal to improve soil health in the Global South.

Contents

1 Introduction

This section begins with an overview of soil quality in the Global South in recent years, followed by a dive into the research gap, understanding where exactly new research is needed, and formulating our research question and a broad step-by-step approach. Finally, the significance of this study and how it can be useful is mentioned.

1.1 Background

In recent decades, the Global South's soil has been in a bad shape; and some of the reasons are unsustainable agricultural practices such as monocropping, overreliance on fertilizers and poor tillage systems, poor water management, deforestation, overgrazing, and industrial pollution. All those contribute to food insecurity, poverty and environmental degradation. Consequently, numerous studies conducted show that conservation techniques like *cover crops*[1], no-till[2], and strategic intercropping[3] can improve nutrient cycling, restore soil organic matter, inhibit weed growth, and eventually increase yields. [Olawepo et al., 2024]

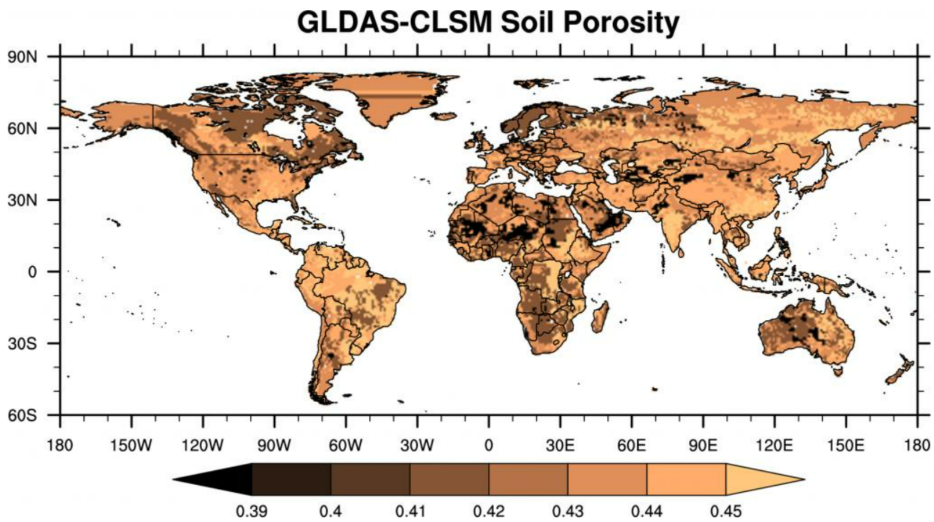

Figure 1: Global Soil Porosity

Figure 1: Global soil porosity map highlighting severely degraded regions in the Global South.

1.2 Research Gap

A large amount of studies explore sustainable practices in isolation (Around a hundred of them on Google Scholar); far fewer studies have a combination of two of those practices in a specific region of a country (8 on Google Scholar, Elicit and other few less reknown research databases), or no combined sustainable farming across ecological zones studies were found. Moreover, while some crops are proven to be efficient in terms of highest biomass producer, best

[1] A crop grown for the protection and enrichment of the soil.
[2] An agricultural technique for growing crops or pasture without disturbing the soil through tillage.
[3] Crops grown among other plants of a different kind, usually in the space between rows.

intercrop booster or best crop for no-tillage systems in some areas, farmers still need distilled, data-driven recommendations considering other criteria alongside such as the crop's hardiness, water needs, temperature needs, machinery needs, labour and soil management needs. Till date, no globally scalable study has been done which covers all those criteria with sustainable farming practices to give practical, well-rounded recommendations to farmers. This is why the term **synergy**[4] is present in the title, as there is an attempt to combine the 3 sustainable practices for a better boosting effect than individually practicing them.

1.3 Research Question and Approach

The Global South heavily relies on agriculture for both export and domestic consumption due to pressures on the global market and its comparative affordability. [Alston and Pardey, 2006] As shown above, the soil is in a critical state, and there is a need to improve this soil quality to help those Global South countries' profitability and mitigate poverty.

This study is exploratory [Edgar and Manz, 2017], and by definition, it is a research that aims to gain more insight or get a better understanding of a situation or phenomenon. In this case, the research question will be:

Which crops are most compatible with cover cropping, intercropping, and no-till systems to improve the soil quality, and which crops are best for each ecological region in the Global South according to environmental data?

First, a structured narrative review is conducted from resources like FAOSTAT, PFAF, Web of Science, Google Scholar, Scopus, and AI tools (e.g. Elicit) using the keywords biomass, [5] cover crops, intercrops, no-till, and Global South. Chapter 2 - Literature Review is going to be responsible to cover this part.

Then the second step, chapter 3 - EDA part, is to analyse and summarise all the top-performing biomass producer crops grouped by their soil type. Then, cross-check their relative tillage yield (No-till system vs. conventional system) and also how allelopathic they are to other species to estimate their intercropability. For important missing values, agronomic data from encyclopedias, notably PFAF, PictureThis, ECOCROP, and FAOSTAT, were utilised. After this process, a shortlist of crops is fed for further analysismulti-criteria scoring and region-wise recommendation which will be discussed in the methodology section in chapter 4. Then we will discuss the results and the recommendations in chapter 5, chapter 6 will consist of the various limitations this study has and which future research could possibly be done to tackle those limitations and finally, chapter 7 - the conclusion.

1.4 Significance

This thesis offers an analysis to help advisers and farmers to select crop combinations that optimise soil health by integrating multi-criteria decision analysis, geospatial mapping, and in-depth research. Though it does not account for country-specific policies, seed access, local knowledge, or resource availability, its transparent, data-driven approach reduces the risk of

[4] Here, let's say cover crop benefit $= 1$, intercrop benefit $= 1$. When mixed together, $1 + 1 \neq 2$, it is > 2.

[5] Organic matter derived from living organisms, like plants and animals, that can be used as a fuel source or for other energy production

incompatible crop choices and supports faster adoption of ecological practicesaligned with our goal of improving soils in the Global South.

2 Literature Review

In this chapter, we will uncover the different sustainable farming practices individually and how helpful it proved to be, then a summary providing facts and figures on different combinations of those sustainable practices is done. The key takeaways are mentioned before a summary table that highlights the synergy - additional benefits that happen when combined with each other.

Individual practices:

Cover Cropping: Cover cropping is one of the agricultural practices that produces the most benefits to the soil health and indirectly the crop production. It can regulate ecosystem services, improve nutrient cycling, and enhance soil fertility. [Quintarelli et al., 2022] Cover crops prevent erosion by providing continuous ground cover, reducing soil detachment due to rainfall and other agricultural water damages [Kaspar and Singer, 2011]. They also contribute to soil organic matter and structure by growing roots and adding residue, which improves water accumulation and absorption. Cover crops also help reduce nutrient losses, particularly nitrate leaching, by capturing excess nitrogen during fallow periods with studies reporting reductions of up to 90% [McCracken et al., 1994]. Finally, they promote soil biodiversity by suppressing weeds and pests through allelopathic effects and improving habitat for beneficial organisms [Inderjit and Keating, 1999].

Intercropping: Intercropping is the cultivation of more than one crop species on a single parcel of land. Intercropping seeks to exploit species complementarities to capture more of the available light, water and nutrient resources, and thus increase combined crop yield. [Stomph et al., 2020] By enabling crops to complement one another in terms of light, water, and nutrient uptake, this technique increases overall resource use efficiency and frequently produces higher combined yields than monocropping [Wopke VAN DER WERF, 2020]. Since intercropping systems increase plant diversity while sealing ecological niches that weeds would otherwise occupy, they have been showed to lessen pest and disease pressures and suppress weeds more successfully . Furthermore, through biological nitrogen fixation, combinations like cereals and legumes can improve soil fertility and promote long-term soil health. [Vlahova, 2022] As a result, intercropping has been praised for its ability to sustainably increase production while maintaining soil quality and ecosystem balance.

No-tillage system: No-till farming, an ecological technique that involves planting crops directly into residue-covered soil without tilling, has transformed agriculture. It covers nearly 25% of cropland in the United States and provides benefits such as reduced soil erosion, improved water efficiency, and potential carbon sequestration [Margulies, 2012], [Triplett and Dick, 2008]. No-till farming enables farmers to manage larger areas with less labour, energy, and machinery. [Triplett and Dick, 2008] However, challenges remain, including increased reliance on herbicides, potential water contamination, and the emergence of herbicide-resistant weeds [Margulies, 2012]. Economic considerations include lower fuel and labour costs, but higher pesticide and specialised equipment costs [Swenson and Johnson, 1982]. While no-till can maintain or improve crop yields when properly managed, ongoing research is required to address its limitations and expand its global application.

Since this is an exploratory thesis, the literature review will consist of showcasing the main key points for further analysis. Few examples were used as there are a lot of combinations of sustainable practices for various crops around various regions and climates.

The implementation of *individual* soil health practices, such as relay intercropping, winter cover crops, and no-tillage, has continuously improved soil structure, infiltration, and organic carbon without reducing yields. For instance, in California's San Joaquin Valley, 15 years of no-till plus cover crops increased aggregation, infiltration, and C stocks [Mitchell et al., 2017]; worldwide data confirm that cover crops under reduced tillage maintain yields and build soil organic matter [Su, 2020]; and relay intercropping of legumes into wheat supplied 3867 kg N ha^{-1} via fixation and increased the subsequent maize crop by 30 %. [Amossé et al., 2014] Integrated systems layer cover crops, living mulches, and intercrops. Reviews emphasise compatibility, sowing time, density, geometry, and termination as crucial to maximise benefits [Dzvene et al., 2023]. Vetch-oat CCs doubled N inputs, and cucumber-snow-pea intercrops obtained mean land-equivalent ratios of 1.19 in on-farm trials throughout a transition gradient in Brazil. The greatest improvements were observed on neutral-pH, high-fertility soils [Stratton et al., 2022]. On-farm trials across a Brazilian transition gradient revealed that vetchoat cover crops doubled soil N inputs, and cucumbersnow pea intercrops achieved a mean land-equivalent ratio of 1.19, with the strongest gains on neutral-pH, high-fertility soils [Stratton et al., 2022]. Meta-analyses warn of allelopathy among distant species and emphasise the importance of trait-based, multi-criteria mixturesbalancing biomass, N fixation, root architecture, and non-interferenceto customise combinations to local soils and climates.

Key takeaways:

- *Individual* practices (no-till, cover crops, relay intercropping) improve soil health without yield being affected.
- *Paired* tactics (legumebroadleaf mixes, cover crops reduced tillage) amplify the crop's physical, biological and chemical benefits.
- *No existing papers* have made a broad worldwide analysis and recommendations of best-performing crops in sustainable farming to enhance soil quality, which is in poor condition and needs to be fixed.

The table below shows how combining practices such as cover cropping, intercropping, and no-tillage provides more benefits - improves nutrient cycling, soil structure, and water retention more effectively - than practising them in isolation.

Table 1: Synergies Between Combined Agroecological Practices

Practices Combined	Study (Context)	Key Synergy
No-till + Cover cropping	Mitchell et al. (15 yr NT + CC, CA)	Soil resilience & water retention; extra organic matter
No-till + Intercropping	Rühlemann & Schmidtke (organic NT)	Field pea + sunflower in NT 1.72.2 Mg ha^{-1} biomass; vetch fixes ~60 kg N ha^{-1}
Cover cropping + Intercropping	Amossé et al. (relayintercrop legumes under wheat, FR)	Relay legumes didnt hurt wheat, doubled N for next crop, +30% maize yield

Also, as a plus, from the literature and analysis, some exceptional mixture synergies needed to be highlighted:

Table 2: Exceptional cover-crop combinations and their key benefits

Crop Combination	Study / Source	Key Benefits
Maize + Italian ryegrass	California SJV no-till cover-crop study [Mitchell et al., 2017]	▪ Fastest infiltration under no-till & ryegrass ▪ Highest aggregate stability & soil respiration ▪ No maize yield penalty
Hairy vetch + Cereal rye	Michigan root-trait study [Bukovsky-Reyes et al., 2019]	▪ Vetch develops fine, high-SRL roots ▪ Rye maintains thick, fibrous roots ▪ Maximizes soil exploration & nutrient capture
Black oats + Common vetch	Six-species winter mix, Brazil [Stratton et al., 2022]	▪ 5 % soil bulk density; 27 % porosity ▪ 300 % saturated hydraulic conductivity ▪ +15 % common-bean yield following mix
Sorghum + Common vetch	Coverintercrop recommendation [Tiruneh et al., 2019]	▪ Early vetch N-fixation boosts fertility ▪ Sorghums deep C roots scavenge residual N ▪ Provides summer mulch for no-till ▪ Strong weed suppression & high biomass
Eucalyptus + Leucaena	Forestryagrosilvopastoral systems [JESUS and and, 1989]	▪ Complementary canopy structures for light interception ▪ Leucaena fixes N to benefit young Eucalyptus ▪ Annual biomass >20 t haź (Eucalyptus) + 12 t haź (Leucaena) ▪ Supports sustainable no-till forestrylivestock integration

3 Initial Exploratory Data Analysis

In this section, the datasets are introduced and the key visualisations of each is discussed and how we used each of them for our further analysis and methodology. We will uncover the steps taken to make a shortlist from the multitude of possible crops for a combination of sustainable farming practices.

Initially, 4 available datasets from Google Datasets were collected, notably:

1. Cover crop dataset on temperate regions, mainly in The Netherlands and other European countries (Wageningen University) From this dataset, the top performing covercrops could be summarized, yielding the most dry matter (Figure shown below), most organic matter (Appendix Figure 6), most Nitrogen uptake (Appendix Figure 7) grouped by soil types cultivated. We take all those top performers and put them in a temporary shortlist.

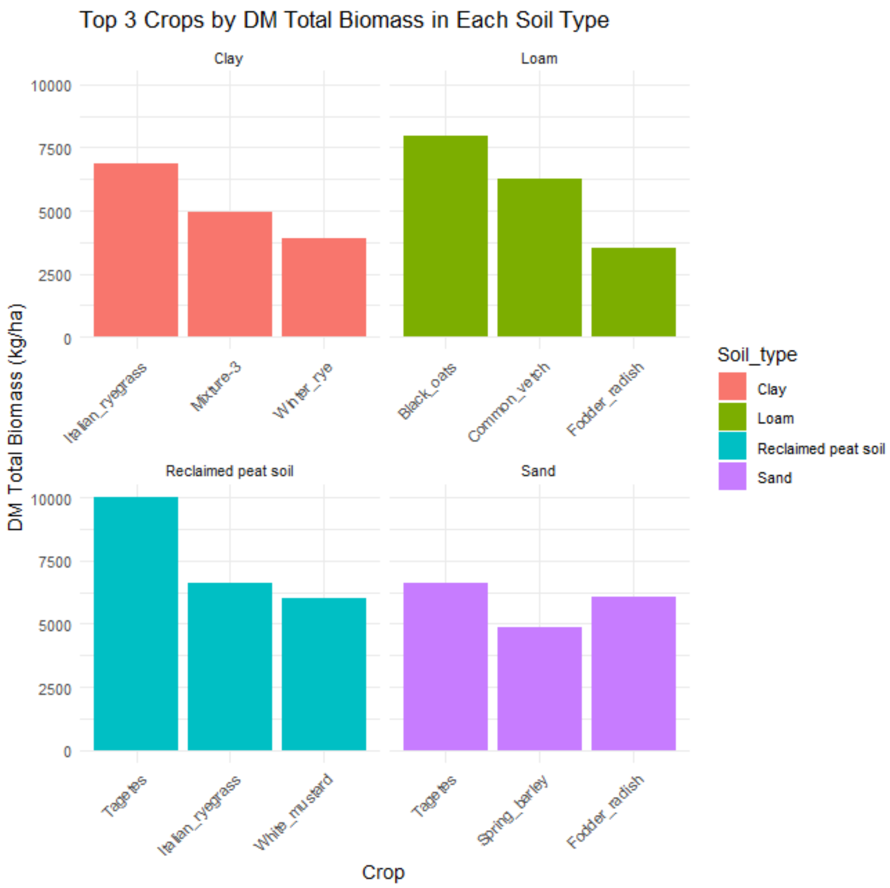

Figure 2: Top Organic Matter Producing Crops by Soil Type

2. Cover crop datasets on temperate and tropical regions around the world (ScientificData) From this dataset, the best biomass-yielding crops can be spotted (Appendix figure 8). The crops selected are the ones suitable for Global South's climate (20°C and above and few countries around 15°C in winter).

Table 3: Top Crops in the Global South by Mean Biomass Yield for Warm Zones

Temperature average	**Crop_type**	**Avg_Yield (t/ha)**
15–20°C	Eucalyptus	22.1
15–20°C	Acacia	19.6
20–25°C	Sugarcane/energycane	19.5
>20°C	Eucalyptus	17.9
>20°C	Leucaena	19.9
>20°C	Casuarina	26.3
>25°C	Napiergrass	53.2
>25°C	Giant reed	32

3. No-till Data for various crops (UMR ECOSYS, AgroParisTech, Université Paris-Saclay)

Figure 9 in the Appendix shows the top crops in the dataset yielding more under no-till systems. The dataset contained few crops only, and no other datasets were freely available. But the dataset was enough to confirm certain trends for a plant to be suitable for no-till. Encyclopedias such as PFAF, PictureThis and ECOCROP were mainly used to estimate the no-tillage system suitability of the remaining crops by matching features for a good no-tillage crop, such as being a good erosion control crop, high biomass producer, allelopathic to repel pests, and, most importantly, small-seeded - to directly implant in the soil with ease - but later developing into big enough to break the ground deep inside, creating space for substances or natural fertilizers and water to be stored [Vincent-Caboud et al., 2017] [Mirsky et al., 2021].

The table below shows some features for a crop to be a good no-tillage crop:

Table 4: Key Traits for No-Till Crops and Their Importance

Trait	**Why It Matters**
High Biomass Production	Biomass provides a thick mulch layer that suppresses weeds and pests, improves soil health, and prevents erosion.
Residue Quality	Wide, fibrous residues that lie flat protect soil, conserve moisture, and ease planter penetration.
Early Vigor	Rapid early growth outcompetes weeds and builds biomass before termination.
Easy Mechanical Termination	Stems that crimp and flatten cleanly under a roller-crimper reduce regrowth and the number of passes required.
N-Supply or Soil Building	Legumes that fix N or species that boost soil biology (earthworms, microbes) over time
Seed Size & Planting Ease	To directly implant in the soil with ease.

4. Allelopathy Dataset [Zhang et al., 2021] to assess intercrop suitability This dataset contains information about how allelopathic a plant species is. Figure 4 below shows the general information about our selected shortlist crop species, and the table below that is the detailed information of Avena Sativa (black oats)one of the shortlisted cropsand which types of species it is allelopathic to can be seen in the figure. From that, the strength of allelopathy can be deduced; If the species in question is allelopathic to only weak plants or not.

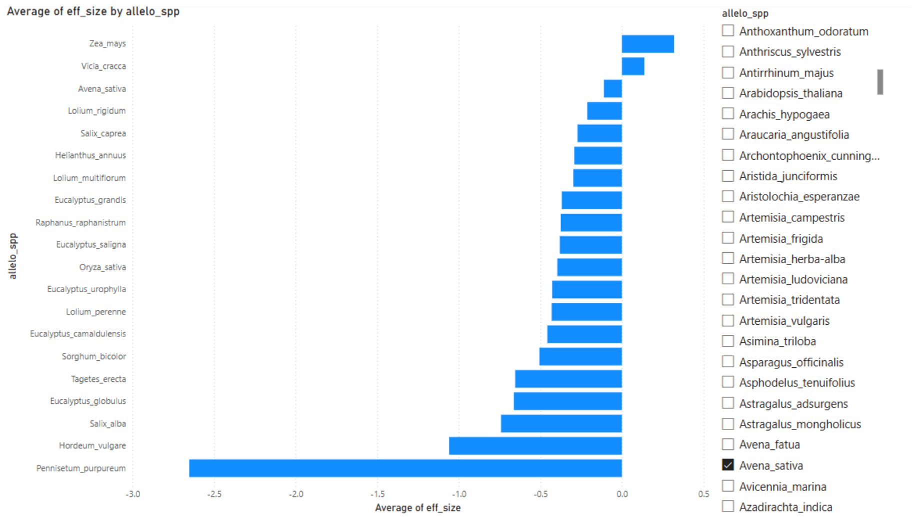

Figure 3: Average Allelopathic strength of selected shortlist crops

Table 5: Intercropping Performance Metrics for *Avena sativa* Companion Species

Species	**Mean Effect**	**Median Effect**	**Pos.**	**Neg.**	**Total**	**Pos.%**	**Neg.%**
Campanula rotundifolia	0.326	0.310	4	2	6	66.7%	33.3%
Capsella bursa-pastoris	0.186	0.219	4	2	6	66.7%	33.3%
Daucus carota	−0.0224	−0.0464	3	3	6	50.0%	50.0%
Poa annua	0.0614	−0.0072	3	3	6	50.0%	50.0%

The same is done to all the species shortlisted above and their intercropping suitability is estimated.

After getting around 50 crops from the cover crops dataset, lots of possible crop alternatives were crossed out due to the low suitability of intercropping and no-tillage systems. In the end, the shortlist consisted of 20 crops for further analysis, discussed in the Methodology section below.

Note: All the datasets had thousands of data points, passing the t-tests easily.

4 Methodology

In this part, we are going more in-depth into the framework used in this study - Multi-criteria Scoring, Sensitivity and robustness analysis to confirm that the weights (own judgement) given to the criteria are admissible and Environmental matching approach.

4.1 Multi-Criteria Scoring

An evaluation for each candidate species using eight agronomic and practical criteria was conducted:

- **Cover-crop suitability (%)** - This criterion aligns directly to our goal of enhancing soil quality since a good cover crop produces high biomass, which is a natural fertilizer for the soil and plant.
- **Intercrop compatibility (%)** - This criterion maximizes yield and quality of crops and soil as a byproduct.
- **No-till adaptability (%)** - This is a key pillar to enhance the soil quality, but due to the difficulty of affording the machinery needed in some Global South countries and the lack of data for every species, the weight of this criterion is reduced despite being a key pillar.
- **Water requirement (1-10)** - Where 1 stands for very low water requirements and 10 refers to constant and heavy water needs, a scale of 5 is the demarcation point where it would start being an issue for the farmers in the Global South.
- **Climatic hardiness (1-10)** - A crop of a hardiness scale of 1 means that the crop can sustain extreme cold conditions, and a scale of 10 means that it can sustain the most extreme hot conditions. The goal is to maximise the scale in our case, and this criterion is very important since the crops need to adapt to the harsh conditions of the Global South.
- **Allelopathic potential (1-10)** - Scale of 1 stands for crop having no or negligible allelopathic behaviour, and a scale of 10 means that the crop is very toxic to other plants, pests, and even humans. Here, penalising occurs after the scale of 3, since after that, it becomes toxic to other plant species.
- **Machinery dependency (1-10)** - A scale of 1 dependency means the crop needs negligible or no machinery to cultivate, but a scale of 10 means that it will need rigorous machinery to be cultivated. After the scale of 5, it will become an issue for some Global South countries.
- **Management and Labour Complexity (1-10)** - A scale of 1 dependency means the crop needs negligible or no labour or soil management to cultivate, but a scale of 10 means that it will need rigorous labour and soil care to be cultivated. After the scale of 5, it will become an issue for some Global South countries.

Variable	Weight	Penalization	Justification
Cover crop suitability (%)	2.0		Aligns directly to our goal of enhancing soil quality
Intercrop suitability (%)	1.5		Key pillar of mixing sustainable farming
No-till suitability (%)	1.0		Key pillar too but difficult to fund machinery and tools
Water need (110)	1.0	$(1+\frac{5-x}{5})*100$ if $x>5$	After 5, it becomes problematic to cultivate in drier areas
Hardiness (110)	2.0		Most Global South countries require strong stress tolerance
Allelopathy (110)	1.0	$(1+\frac{3-x}{5})*100$ if $x>3$	Beyond a severity of 3, the crop can inhibit neighbors, after scale of 8, it's too toxic
Machinery dependency (110)	1.0	$(1+\frac{5-x}{5})*100$ if $x>5$	Above 5, high equipment needs may limit adoption
Soil management difficulty (110)	1.0	$(1+\frac{5-x}{5})*100$ if $x>5$	Above 5, difficult conditions limit practical cultivation

Table 6: Criteria weights, penalization factors, and justifications for the multi-criteria scoring.

Below is a table to summarise the weights given and the justification for the weights, the weights were estimated by the researcher. Later in the methodology part there is a robustness and weights perturbation of 50% test used to support the judgements presented.

Those criteria were aggregated properly (applied set of base weights) into a "Suitability" index for each crop, they were normalised (all scaled between 0-100) and were ranked by the highest Suitability Index.

4.2 Sensitivity and Robustness analysis

To ensure that the rankings were not biased with the subjective weight choices, a Monte Carlo sensitivity test was conducted. In 10,000 iterations, each base weight was randomly perturbed by 25% at first, renormalized to sum to one, and used to recompute it's Suitability index. The ranks were recorded by the crop's rank position per iteration, and the result of the 10,000 iterations was summarized by a boxplot of the crops' rank position. Later, the sensitivity was changed to 50%, and it was still robust, having more or less the same output. This suggests that even though there were missing values, the researcher's judgment for the sustainable practices' (cover crop, intercrop and no-till) suitability was robust and reliable, ensuring that any potential bias from the subjective weighting has minimal impact on optimal crop recommendations. A confidence scores table or range annotations are not needed.

4.3 Environmental Matching

Various maps were collected for this section, notably, soil percentage maps around the world (clay, silt and sand), world water availability, and world hardiness maps as shown in the Appendix (Figure 10 to Figure 14). Intersecting all those maps, similar ecological zones in the Global South can be separated and outlined. Now, the next step is to consult the plant encyclopedia again - mainly PictureThis - which had world maps of where the crops were cultivated. The data available there helps us spot where ideally those plants are cultivated and in which conditions they thrive, thus allowing for a good recommendation of the crops in the different ecological zones.

Map sources: [USDAAPHISPPQCPHST, 2012] [NGSDISSC, 2020] [glo, 2025]

5 Results & Recommendations

This section consists of the results of the methodologies and the optimal recommendations across ecological zones in the Global South.

The figure below shows the Monte Carlo boxplot output:

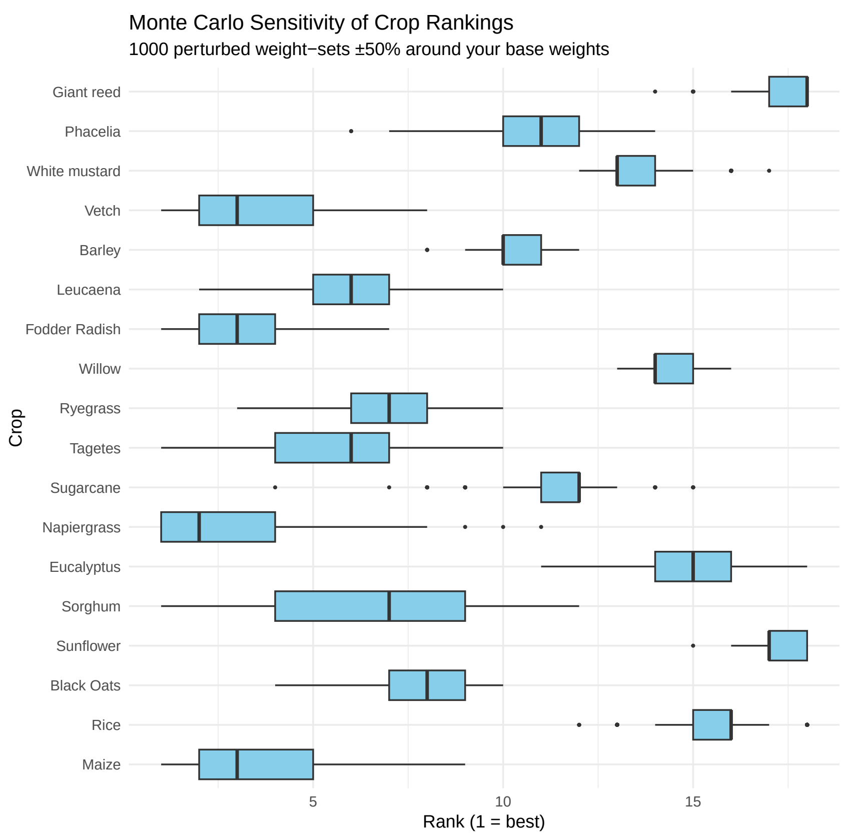

Figure 4: Monte Carlo output

From this figure, a nice shortlist of the top 10 crops is obtained, with a significant difference from the other crops. There was no need to implement a confidence scores table or range annotations since the random field perturbation of weights is by ś50% from the base weight with 10,000 iterations. The shortlisted crops are Napier grass, vetch, rye, sorghum, barley, phacelia, leucaena, fodder radish, tagetes, black oats, and maize. Those mixes of crops on the shortlist are well-rounded for the different ecological zones around the world at first glance. So, there is no need to add runner-ups to the shortlist as well.

The tables below will summarise the final results concluded:

The intersections of the Raster graphic maps were messy and difficult to differentiate. Access to map databases would really help to understand, the table below shows how ecological regions in the Global South was formed for this study:

Table 7: Summary of criteria used to define each ecological region via intersecting global hardiness, soiltexture, rainfall, and wateravailability datasets.

Ecological Region	Delimiting Data Layers & Criteria
Tropical Humid Zone	USDA Hardiness Zones 1013; annual rainfall >1500 mm; GLDAS silt & clay >0.4; water availability >3000 mș/yr.
Tropical Semi-arid / Savanna Zone	Hardiness Zones 1112; rainfall 8001200 mm/yr; GLDAS sand 0.40.6; freshwater stress 10002000 mș/yr.
Tropical Highlands / Subtropics	Zones 911 (cooler isotherms); rainfall 10002000 mm/yr; loamsilty-clay (silt 0.30.5); water availability 20005000 mș/yr.
Warm Temperate Zones	Zones 810; rainfall 6001200 mm/yr; loamy soils (sand 0.20.5, silt 0.30.5); water availability 20005000 mș/yr.
Tropical Coastal / Island Zones	Zones 1113; rainfall >2000 mm/yr; high coastal sand >0.6; marinemoderated stable warmth.
Arid / Dryland Tropics	Zones 1213; rainfall <500 mm/yr; very sandy soils >0.7; water scarcity <1000 mș/yr.

Table 8: Ecological Zones and Example Global South Regions

Ecological Zone	Example Regions
Tropical Humid Zone	Congo Basin (DR Congo, Cameroon), Indonesian Archipelago (Sumatra, Kalimantan), Equatorial Amazon (Brazil, Peru)
Tropical Semi-Arid / Savanna Zone	Sahel (Mali, Niger, Chad), Northeastern Brazil (Ceará, Piauí), Central India Plateau (Madhya Pradesh, Maharashtra)
Tropical Highlands / Subtropics	Ethiopian Highlands (Amhara, Oromia), Andean Highlands (Peru, Bolivia), Southern Indian Highlands (Karnataka, Tamil Nadu)
Warm Temperate Zones	South Africa (KwaZulu-Natal, Eastern Cape), Southern Brazil (Rio Grande do Sul, Paraná), Northern Mexico (Chihuahua, Coahuila)
Tropical Coastal / Island Zones	Madagascar (East Coast), Philippines (Visayas, Mindanao), Pacific Islands (Fiji, Solomon Islands)
Arid / Dryland Tropics	Pakistan (Sindh, Balochistan), Sudan (Khartoum, Darfur), Namibia (Namib Desert region)

The following table shows the top crops recommended for **Tropical Humid Zones** - typically high rainfall, loamy/silty soils, warm and humid year-round:

Table 9: Crops for Tropical Humid Zones

Selection	Key Strengths
Napiergrass	Thrives in high rainfall (10001500 mm); tolerates humid tropics; excellent forage grass.
Barley (Winter)	Adaptable to wide altitude range; grows in moderate rainfall and tolerates high salinity.
Leucaena	Deep-rooted legume; thrives in high rainfall and poor soils; nitrogen fixer and erosion controller.

The following table shows the top crops recommended for **Savanna Zone** - typically seasonal rainfall, sandy-loam soils, moderate fertility:

Table 10: Crops for Savanna Zone

Selection	Key Strengths
Sorghum	Excellent drought and heat tolerance; suitable for low to moderate rainfall.
Maize	Fast-growing cereal; high yield in moderate fertility and rainfall zones.
Tagetes	Tolerates low rainfall; performs well in light soils; also used as pest repellent.

The following table shows the top crops recommended for **Subtropics**- typically Cooler nights, fertile volcanic soils, varied rainfall.

Table 11: Crops for Subtropics

Selection	Key Strengths
Fodder radish	High rainfall adaptability; deep rooting for nutrient recycling; tolerates diverse soils.
Common Vetch	Nitrogen fixer; suitable for light to medium soils; tolerates cooler subtropical climates.
Ryegrass	Versatile grass for forage; good cold tolerance; adapts to wide altitude and rainfall ranges.

The following table shows the top crops recommended for **Warm Temperate Zone** - Mild winters, hot summers, mix of loam/sand:

Table 12: Crops for Warm Temperate Zones

Selection	**Key Strengths**
Common Vetch	Performs well in temperate climates; improves soil fertility; supports biodiversity.
Maize	Adaptable; thrives in well-drained soils and warm temperatures.
Black Oats	Excellent cover crop; cold-tolerant; suppresses weeds and recycles nutrients.

The following table shows the top crops recommended for the **Tropical Coastal Zone** - typically high rainfall, often sandy or erodible soils, and salinity in places:

Table 13: Crops for Tropical Coastal Zones (Avoid Waterlogging)

Selection	**Key Strengths**
Leucaena	Salt-tolerant; fast-growing tree legume; stabilizes coastal soils.
Napiergrass	High biomass forage; good erosion control; tolerates high humidity.
Fodder radish (Avoid waterlogging)	Great cover crop; Deep-rooted; breaks compacted layers

The following table shows the top crops recommended for **Dryland Tropics** - typically low rainfall, poor sandy soils, high evaporation:

Table 14: Crops for Dryland Tropics

Selection	**Key Strengths**
Sorghum + Cowpea	Highly drought-tolerant combo; improves soil fertility and food security.
Leucaena	Tolerates low rainfall; improves degraded land; multiple uses including fodder and firewood.

6 Study Limitations

Approaching the end, limitations found while doing this study is listed and the future research directly or indirectly related to those limitations is provided.

Data Gaps There was very little variety of crops in the no-till vs conventional till dataset. And while the allelopathy dataset was very rich, there were still some species' data missing. To fill these gaps, there was a reliance on trusted secondary sources (PFAF, ECOCROP, FAOSTAT, agronomic encyclopedias) to estimate best-estimate suitability scores. To mitigate bias, Monte Carlo sensitivity test (up to 50% weight perturbations) was used, which revealed that despite these imputations, the top-performing crops maintain a stable high ranking, giving our conclusions credence even when raw data is unavailable.

Socio-Economic and Institutional Factors

- **Equipment, Labor & Input Requirements.** This study did not explicitly model the differing labor demands, machinery dependencies, or seed-procurement realities faced by smallholders in specific countries.
- **Knowledge Transfer & Seed Availability.** Local knowledge, extension services, and dependable seed systems are essential for adoption. Even if a crop has high biomass and N-fixation ratings, it may not be widely adopted if seed is hard to come by or farmers are not trained in species-specific management.
- **Policy & Market Incentives.** This study didn't account for the various policy challenges, such as the resilience of investing into knowledge transfer for these mixed sustainable practices and the legalization of importing those seeds (since some countries deem some seeds invasive even if they are not). And on the other hand, this study didn't account for environmentscarbon credits, minimum-price supports, and subsidies provided by the government or external funding bodies.

Trade-Offs Between Short-Term Profitability and Long-Term Soil Health Prioritizing soil health by planting the recommended crops rather than their own cash crops might reduce the short-term profitability of the farmers. Some farmers might be resilient to this risk even though knowledge is transferred that it's better for the long-term profitability.

Future Research Directions and Recommendations

1. **Field Validation Across Agroecological Zones.** The top species (and prospective runners-up) should undergo duplicated on-farm experiments under various soil textures, pH levels, and rainfall regimes in order to adjust our global suitability scores to local conditions.
2. **SocioEconomic Evaluation.** Evaluate the willingness to adopt such practices to prioritize soil health, the challenges they face and create cost-benefit models and incentive programs (such as carbon credits and subsidies) to balance immediate financial gain with long-term improvements in soil health.

3. **Policy Engagement** Work together with development agencies and agricultural ministries to include our multi-criteria framework into national crop-diversification recommendations and to support financing mechanisms (microcredit, output-price subsidies) that reduce the entry barrier for the adoption of cover crops and no-till.

7 Conclusion

This study proposes a practical new model that integrates ecological crop features with the synergistic interactions and advantages associated with cover cropping, intercropping, and no-till systems, exceeding individual sustainable practices methods. By combining multi-criteria scoring with geospatial matching, this framework provides most suitable crops (that we have data on) that can contribute to improving soil quality across different ecological zones. Although the model demonstrates promising combinations, to implement the findings, field validations need to be done and local socioeconomic conditions needs to be considered.

Furthermore, although national agricultural agencies and organizations (FAO) provide crop-specific recommendations, they do not offer comprehensive, zone-specific suggestions that considers both agronomic synergy and local cultivation limitations, which are present in this study.

However, there are some limitations to using this framework. Some data was incomplete, specifically for no-tillage suitability, and they necessitated well-informed estimations from reliable encyclopedias. Despite using a Monte Carlo robustness test to reduce or eliminate the possibility of bias, additional field validation across soil types and other necessary conditions is essential to prove these assumptions.

Furthermore, socioeconomic limitations are a major obstacle. For instance, while leucaena and Napier grass are very effective at stabilising the soil and producing biomass, their economic benefits are either recurrent or nonexistent. Therefore, factors like market demand, seed availability, or smallholder farmers' lack of experience may make it more difficult for them to adopt the recommended crops. For that, incentive programs and subsidies would be very helpful.

Additionally, examining the dynamics of gender roles in terms of labour, training, and inputs will be important to fair adoption, given the crucial role that women play in smallholder systems throughout South Asia and sub-Saharan Africa.

Overall, this thesis presents a data-driven, integrative methodology that combines environmental, geospatial, and agronomic research. A multi-criteria decision framework which has been supported by thorough sensitivity analysis provides methodological transparency and robustness of estimates. In some of the most vulnerable farming systems on the planet, this work offers a scalable framework for improving soil health and resilience by converting complicated ecological interactions into practical crop recommendations matched to various agroecological zones.

8 Datasets and Encyclopedias

Datasets

- **Temperate Cover Crops (Europe)**: The data is mainly from observations in the Netherlands and a few from other European countries - Wageningen University researchers [Norén et al., 2023].
- **Global Cover Crops**: A dataset consisting of biomass yield and reference data for cover crops globally [Ciais et al., 2018].
- **Tillage Systems Comparison**: A global-scale dataset comparing conventional tillage v/s no-tillage systems [Su, 2020].
- **Allelopathy Meta-Analysis**: A dataset used to study allelopathic behaviors between species [Zhang et al., 2021].

Encyclopedic Tools and Databases

- **PictureThis**: A plant app which contains lots of information such as where the plants were native, introduced, invasive and their traits, conditions to survive, sizes and more.
- **PFAF (Plants For A Future)**: An online database offering detailed plant attributes, especially useful for assessing allelopathic traits and no-till suitability.
- **ECOCROP**: A database containing detailed data of crop's attributes and conditions they thrive.

References

[glo, 2025] (2025). Global per capacity water availability. Infographic on freshwater availability and per capita use globally. Accessed May 30, 2022.

[Alston and Pardey, 2006] Alston, J. M. and Pardey, P. G. (2006). Developing-country perspectives on agriculture r&d: New pressures for self-reliance. In Pardey, P. G., Alston, J. M., and Piggot, R. R., editors, *Agricultural R&D in the Developing World: Too Little, Too Late?*, chapter 2, pages 11–28. International Food Policy Research Institute.

[Amossé et al., 2014] Amossé, C., Jeuffroy, M.-H., Mary, B., and David, C. (2014). Contribution of relay intercropping with legume cover crops on nitrogen dynamics in organic grain systems. *Nutrient Cycling in Agroecosystems*, 98(1):1–14.

[Bukovsky-Reyes et al., 2019] Bukovsky-Reyes, S., Isaac, M. E., and Blesh, J. (2019). Effects of intercropping and soil properties on root functional traits of cover crops. *Agriculture, Ecosystems Environment*, 285:106614.

[Ciais et al., 2018] Ciais, P., Peng, S., Makowski, D., and Li, W. (2018). Bioenergy crop yield data and reference.

[Dzvene et al., 2023] Dzvene, A. R., Tesfuhuney, W. A., Walker, S., and Ceronio, G. (2023). Management of cover crop intercropping for live mulch on plant productivity and growth resources: A review. *Air, Soil and Water Research*, 16:11786221231180079.

[Edgar and Manz, 2017] Edgar, T. W. and Manz, D. O. (2017). *Chapter 4 – Exploratory Study*. Syngress.

[Inderjit and Keating, 1999] Inderjit and Keating, K. I. (1999). Allelopathy: Principles, procedures, processes, and promises for biological control. *Advances in Agronomy*, 67:141–231.

[JESUS and and, 1989] JESUS, R. M. D. and and, J. S. B. (1989). Eucalyptus-leucaena mixture experiment. i. growth and yield. *International Tree Crops Journal*, 5(4):257–269.

[Kaspar and Singer, 2011] Kaspar, T. C. and Singer, J. W. (2011). The use of cover crops to manage soil. https://api.semanticscholar.org/CorpusID:127829926. Accessed: 2025-06-28.

[Margulies, 2012] Margulies, J. (2012). No-till agriculture in the usa. *Organic Fertilisation, Soil Quality and Human Health*, 9:11–30.

[McCracken et al., 1994] McCracken, D., Smith, M., Grove, J., MacKown, C., and Blevins, R. (1994). Nitrate leaching as influenced by cover cropping and nitrogen source. 58(5):1476–1483.

[Mirsky et al., 2021] Mirsky, S. B., Cavigelli, M. A., Ryan, M. R., Reberg-Horton, C., Ackroyd, V. J., and Silva, E. M. (2021). A practical guide to no-till and cover crops: 2nd edition. Accessed: 2025-05-16.

[Mitchell et al., 2017] Mitchell, J. P., Shrestha, A., Mathesius, K., Scow, K. M., Southard, R. J., Haney, R. L., Schmidt, R., Munk, D. S., and Horwath, W. R. (2017). Cover cropping and no-tillage improve soil health in an arid irrigated cropping system in californias san joaquin valley, usa. *Soil and Tillage Research*, 165:325–335.

[NGSDISSC, 2020] NGSDISSC (2020). GLDAS Soils. Accessed on May 30, 2025.

[Norén et al., 2023] Norén, I. S., van Geel, W., de Haan, J., Dekkers, M.-F., and Haagsma, W. (2023). Biomass production and nutrient content of temperate cover crops.

[Olawepo et al., 2024] Olawepo, G. K., Kolawole, O. S., and Isah, J. O. (2024). *Threat to Soil Health and Productivity in the Global South*, pages 283–316. Springer Nature Singapore, Singapore.

[Quintarelli et al., 2022] Quintarelli, V., Radicetti, E., Allevato, E., Stazi, S. R., Haider, G., Abideen, Z., Bibi, S., Jamal, A., and Mancinelli, R. (2022). Cover crops for sustainable cropping systems: A review. *Agriculture*, 12(12):2076. Academic Editor: Manuel Ângelo Rosa Rodrigues. Received: 1 November 2022; Accepted: 30 November 2022; Published: 3 December 2022.

[Stomph et al., 2020] Stomph, T. J., Dordas, C., Baranger, A., de Rijk, J., Dong, B., Evers, J., Gu, C., Li, L., Simon, J., Jensen, E. S., Wang, Q., Wang, Y., Wang, Z., Xu, H., Zhang, C., Zhang, L., Zhang, W. P., Bedoussac, L., and van der Werf, W. (2020). Designing intercrops for high yield, yield stability and efficient use of resources: Are there principles? *Advances in Agronomy*, 160:1–50.

[Stratton et al., 2022] Stratton, A. E., Comin, J. J., Siddique, I., Zak, D. R., Dambroz Filipini, L., Rodrigues Lucas, R., and Blesh, J. (2022). Assessing cover crop and intercrop performance along a farm management gradient. *Agriculture, Ecosystems Environment*, 332:107925.

[Su, 2020] Su, Y. (2020). A global dataset for crop production under conventional tillage and no tillage systems.

[Swenson and Johnson, 1982] Swenson, A. L. and Johnson, R. G. (1982). Economics of no-till crop production. *North Dakota farm research*.

[Tiruneh et al., 2019] Tiruneh, A., Abebe, B., and Demsew, Y. (2019). Evaluation of under sowing vetch in sorghum for intensifying existing sorghum production system in gumara-maksegnit watershed, north gondar, ethiopia. In *Proceedings of the 10th Annual Regional Conference on Completed Crop Research Activities*, pages 392–401.

[Triplett and Dick, 2008] Triplett, G. B. and Dick, W. A. (2008). No-tillage crop production: A revolution in agriculture! *Agronomy Journal*, 100.

[USDAAPHISPPQCPHST, 2012] USDAAPHISPPQCPHST (2012). Global plant hardiness zones. https://nappfast.org/. WGSGCS1984, NAPPFAST 2012, map by David Borchert, USDAAPHISPPQCPHST, Raleigh NC, August 31, 2012.

[Vincent-Caboud et al., 2017] Vincent-Caboud, L., Peigné, J., Casagrande, M., and Silva, E. M. (2017). Overview of organic cover crop-based no-tillage technique in europe: Farmers practices and research challenges. *Sustainability*, 9(5). Received: 8 February 2017; Accepted: 28 April 2017; Published: 4 May 2017.

[Vlahova, 2022] Vlahova, V. (2022). Intercropping – an opportunity for sustainable farming systems: A review. *Scientific Papers. Series A. Agronomy*, 65(1). ISSN CD-ROM 2285-5793; ISSN Online 2285-5807; ISSN-L 2285-5785.

[Wopke VAN DER WERF, 2020] Wopke VAN DER WERF, Chunjie LI, W.-F. C. F. Z. (2020). Intercropping enables a sustainable intensification of agriculture. *Frontiers of Agricultural Science and Engineering*, 7(3):254.

[Zhang et al., 2021] Zhang, Z., Liu, Y., Yuan, L., Weber, E., and van Kleunen, M. (2021). Effect of allelopathy on plant performance: a meta-analysis. *Ecology Letters*, 24(2):348–362.

Author (Year)	Context	Methodology	Key Findings
Mitchell et al. (2017)	CA, irrigated arid rotation	15-yr NT vs ST ±CC; soil assays	NT+CC aggregation, infiltration, SOC; yields maintained.
Nascente et al. (2013)	Subtropical rice, Brazil	3-yr CCrice; NTS vs CTS; SOM fractions	NTS light SOM fractions; pearl millet CC highest C/N.
Amossé et al. (2014)	Organic wheatmaize rotation, SE France	6-site relay-legume intercropping	Wheat yields unaffected; subsequent maize 30 %; Ndfa 3867 kg N ha^{-1}.
Rühlemann & Schmidtke (2015)	Organic no-till vs reduced-till, Germany	2-yr five-legume ±sunflower companion	Field pea biomass 1.72.2 Mg DM ha^{-1}; common vetch fixed 60 kg N ha^{-1}.
Pott et al. (2023)	Subtropical no-till, Brazil	3-yr: oat monocrop, oat+turnip bicrop, 6-species mix; soil physics + bean yields	6-mix BD 5 %, air-filled porosity 27 %, Ks 3Œ; bean yield + 15 %.
Bukovsky-Reyes et al. (2019)	Organic farms, Michigan, USA	On-farm rye vs rye/vetch root trait comparisons	Mix: vetch SRL 4366 %; rye maintained conservative root diameters (DC :N trade-off).
Stratton et al. (2022)	14 farms along agroecological gradient, S Brazil	2-yr vetchoat CC + cucumberpea intercrops; SEM	Cover crops doubled soil N inputs; agroecological sites mineralization 2Œ; intercrop LER 1.191.27.

Table 15: Key field and on-farm studies on combined soil-health and productivity innovations.

9 Appendix

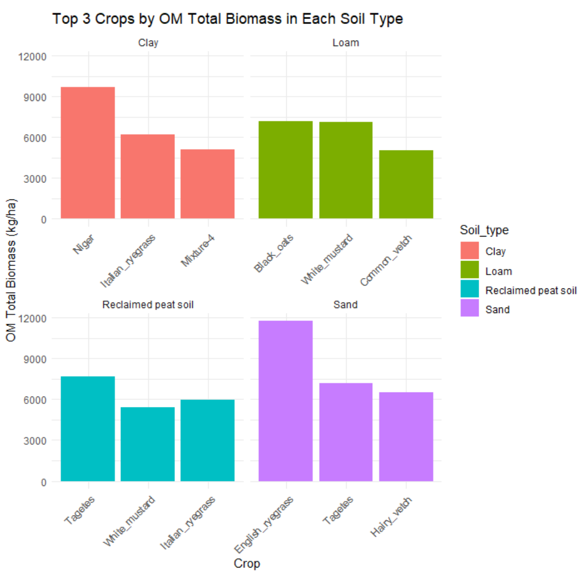

Figure 5: Top organic matter producers by soil type

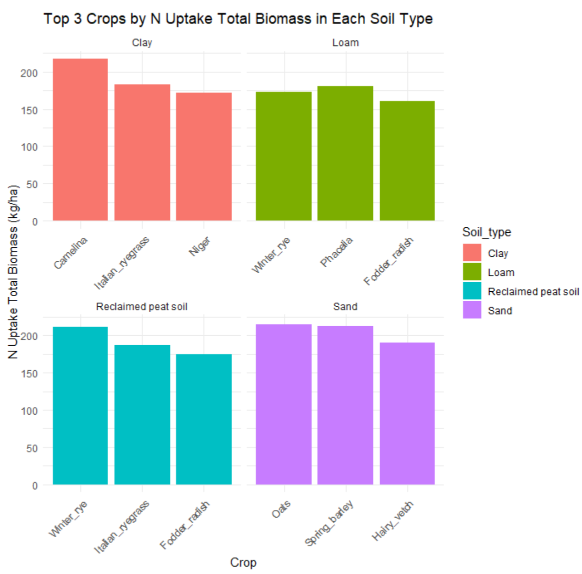

Figure 6: Top N uptake producers by soil type

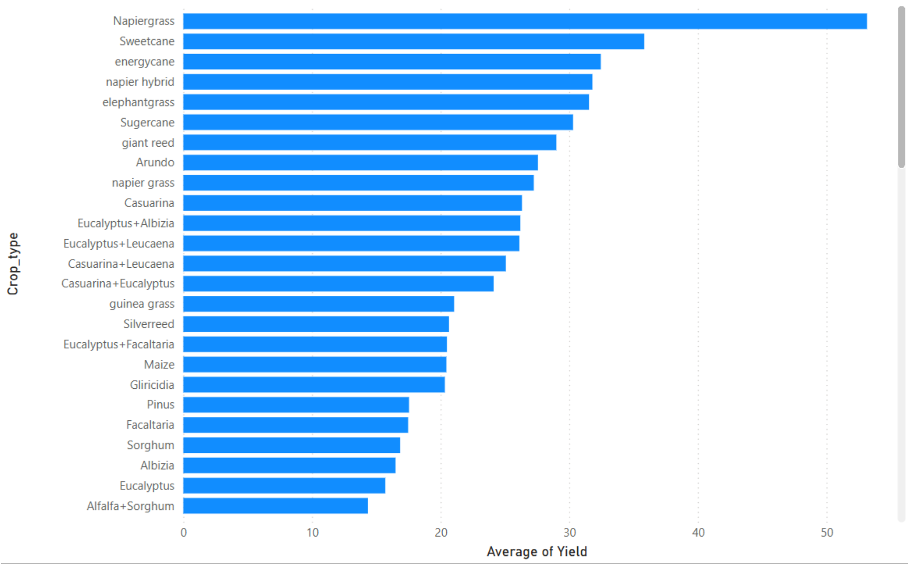

Figure 7: Top biomass producers

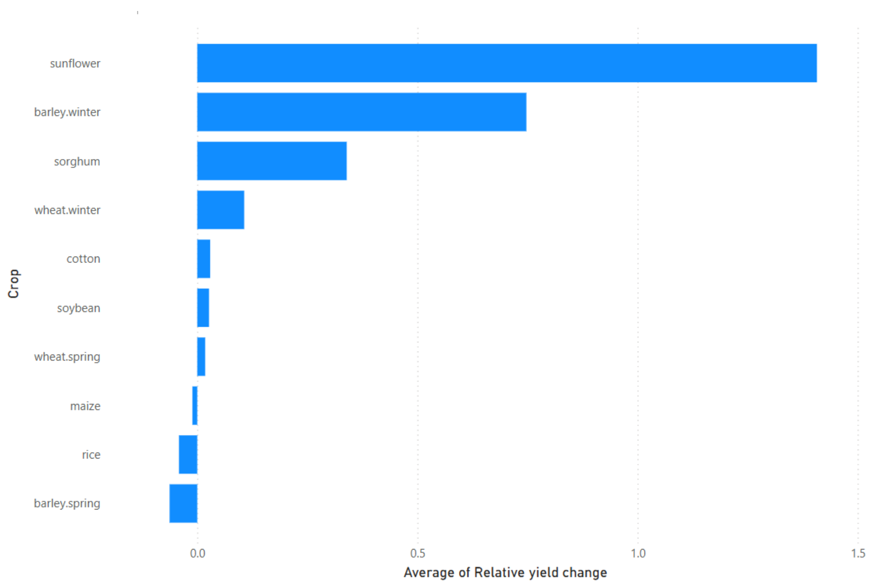

Figure 8: Top no-tillage systems crop

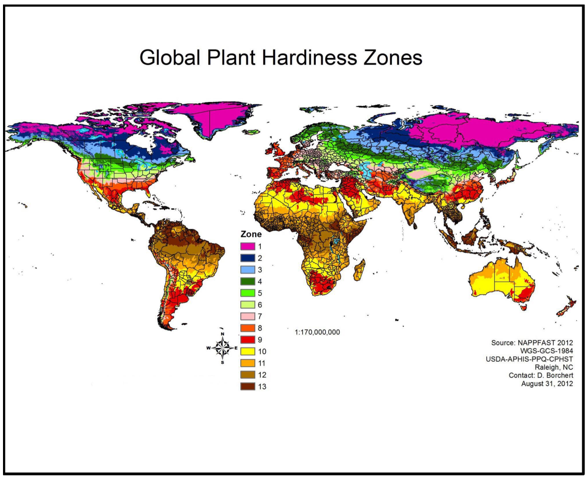

Figure 9: Map overlay

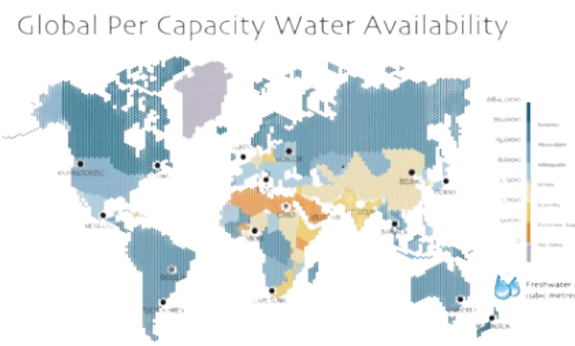

Figure 10: Map overlay

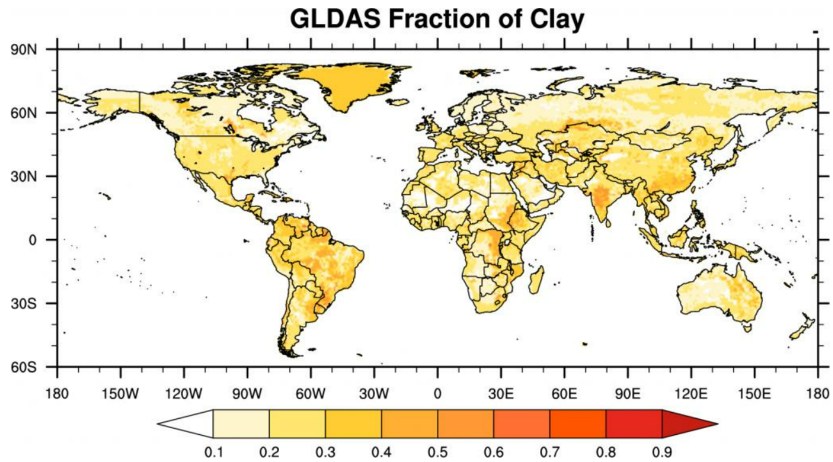

Figure 11: Map overlay

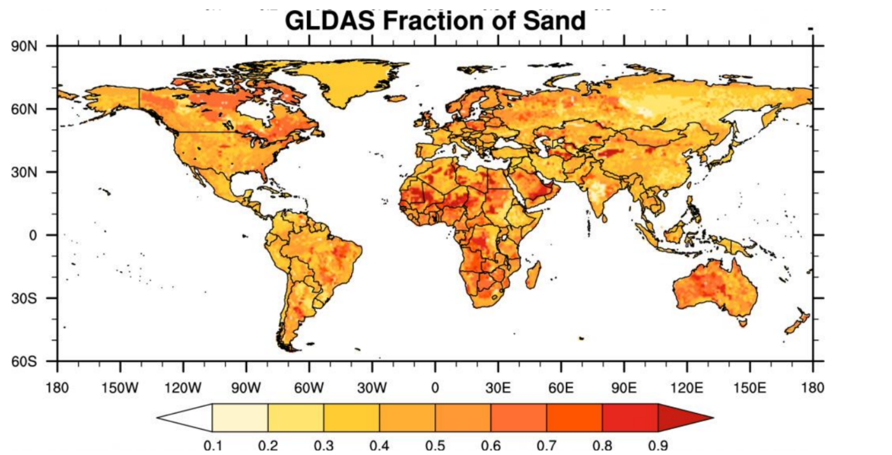

Figure 12: Map overlay

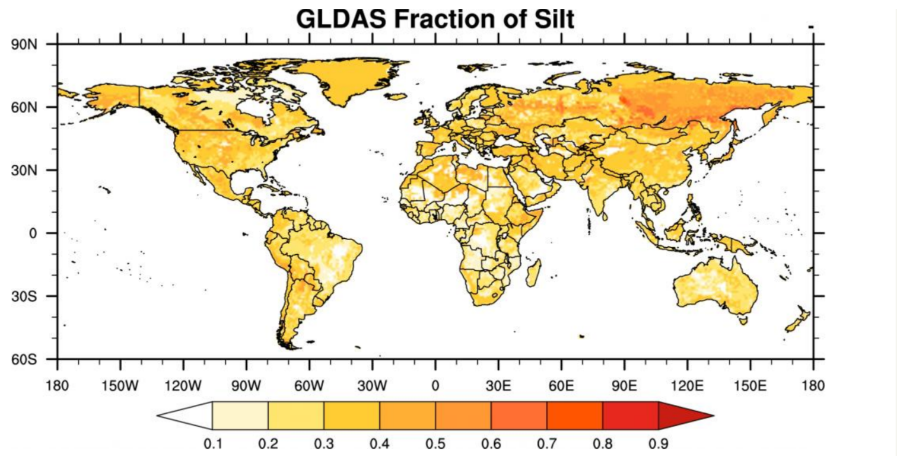

Figure 13: Map overlay