A Functional Trait Approach to Inform Decision-making of Multifunctional Guilds in Food Forestry

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Abstract

The industrial food system is characterized by unsustainable practices, making it an important driver of the current environmental problems. In contrast, alternative food systems such as food forests can address some of these challenges in various ways. They have the potential to provide multiple ecological functions. However, how species should be combined in food forests to gain these benefits is still hardly researched. Therefore, this study uses functional traits (characteristics that influences species and ecosystem functioning (Dawson et al., 2021)) to gain insight into how multifunctional guilds (small group of plants promoting multiple ecological functions) can be created. Seventy promising food forest species characterized by eleven functional traits were selected and analyzed with respect to specific ecological functions. A principal component analysis (PCA) was conducted to observe synergies and trade-offs at species level. This information was used to create a visual overview on how species differ in their ability to support different ecological functions. It revealed a strong correlation between the ecological functions soil fertility and water regulation, as well as, between erosion control and carbon sequestration, meaning that species that provides one function also provide the other. However, carbon storage did not exhibit significant overlap with the other analyzed functions. Each species was scored based on the extent to which it promotes specific ecological functions. To illustrate how this information can be used, four multifunctional guilds, highlighting how different species compositions can lead to distinct outcomes regarding ecological functions, were created. This approach demonstrated the effectiveness of the functional trait approach as a valuable tool for promoting ecological functions within guilds. Furthermore, the methodology presented here can be extended to other species, functional traits, and ecological functions, facilitating the exploration and application of similar concepts in diverse contexts.

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Introduction

The industrial food system is characterized by unsustainable practices, making it an important driver of the current environmental problems. It contributes to the exceedance of the ecological planetary boundaries, including global warming, nitrogen cycle disruption, land use change and species extinction (Björklund et al., 2019). Dependency on fossil fuels, mineral fertilizers and chemical pesticides add to this issue (Średnicka-Tober et al., 2016). Further, economic inequalities across the value chain and adverse effects on human health can be observed (Albrecht & Wiek, 2021).

In contrast, alternative food systems such as food forests can address some of these challenges in various ways. They have the potential to regulate and support the environment, produce healthy food and sufficient livelihoods, and provide sociocultural services such as spaces for recreation, education, and community building (Albrecht & Wiek, 2021).

Food forestry is commonly practised in indigenous and traditional production systems in the tropics and subtropics (called home gardens) and is probably among the oldest forms of agriculture practiced by humanity (Kumar & Nair, 2004; Pilgrim et al., 2018). In temperate climates, however, "forest gardens" developed only in the 1970s (Hart, 1996). This is the reason why food forests are relatively young in this climate. Since these systems take decades to fully develop and come into production, it is only logical that there is not much scientific knowledge of the functioning of food forests in temperate climates. There are several books explaining the design and implementation of food forests. However, there is currently no standardized framework that combines experimental data and interdisciplinary research of the disciplines of ecology and agronomy. Such framework could help to guide the decision-making process in food forest design (van Eijk, 2021).

Food forests integrate nature and food production (Pilgrim et al., 2018) and can be described as a multifunctional biodiverse agroforestry system (Albrecht & Wiek, 2021). A food forest is designed on the structure of young natural woodland (Crawford, 2010), meaning it consists of several plant layers (see Figure 1) of different heights (including trees, shrubs and groundcover) (Albrecht & Wiek, 2021). This system uses mainly perennial plants with direct and indirect benefits to people, all planted to grow together in beneficial mutualism (Crawford, 2010). Due to its high diversity, this system can have multiple benefits sourcing from the different characteristics of the multiple species present in the food forest.

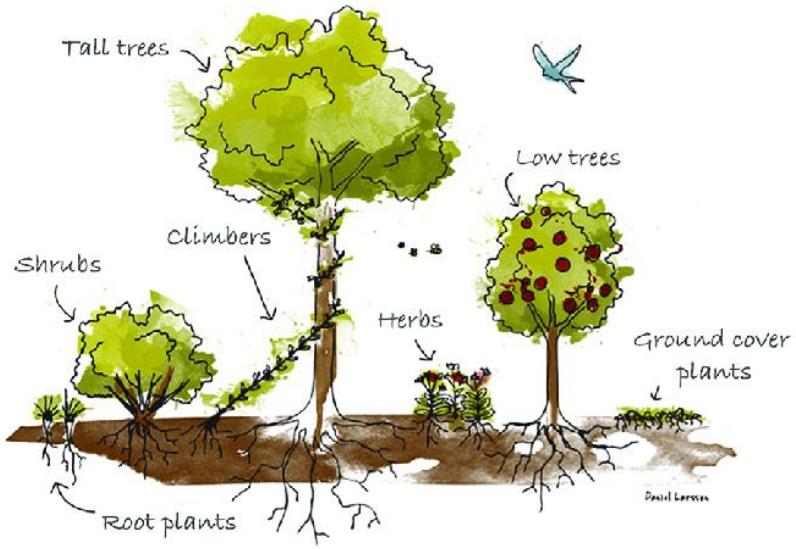

Figure 1: Layers of a food forest (Stoltz & Schaffer, 2018)

Food forestry is one of the most complex forms of agroforestry (van Eijk, 2021), agroforestry being the umbrella term for land-use systems that grows trees together with crops and/or animals (Rebisz, 2019). Figure 2 shows that food forests are a form of agriculture that mimics natural processes and is, therefore, closest to natural systems (Rebisz, 2019). However, in the field of agroforestry, also due to their complexity, food forests are the least studied systems, resulting in significant knowledge gaps on their performance as compared to industrial agriculture systems (Mayor et al., n.d.).

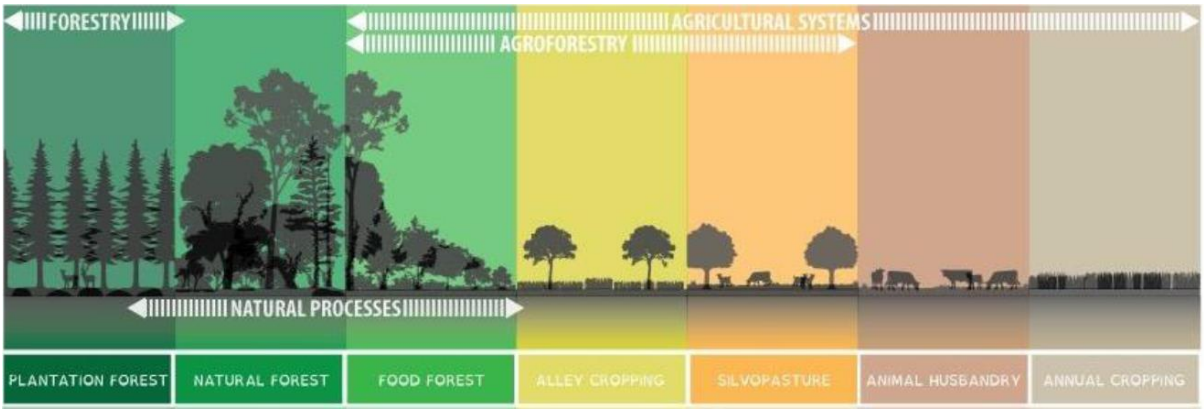

Figure 2: Agriculture and forestry systems adapted from (Stichting Voedselbosbouw, 2023)

In the Netherlands, Wouter van Eck pioneered the food forestry movement in 2009 when he first set up his educational food forest in Groesbeek (Swart, 2022). Currently, the interest in this concept has risen significantly (de Groot, 2017). In 2017, the Dutch government signed the Green Deal of Food Forest, acknowledging the concept of food forests being part of "green growth" (RVO, 2017). Nevertheless, there is limited knowledge of the design of Dutch food forests (Swart, 2022).

As mentioned above, it can be argued that the diversity in food forests can potentially have multiple benefits as compared to a monoculture. However, how species should be combined in food forests to gain these benefits is still hardly researched. Guilds can be used as a design tool for plant selection in food forests (Jacke & Toensmeier, 2005). A Guild can have multiple meanings depending on the application of the word. In ecology, a Guild is defined as "a group of species that exploit the same class of environmental resources in a similar way." (Hawkins & MacMahon, 1989). This is different to how this term is used in the context of food forestry. Dave Jacke (2021) defined a Guild as “a set of plants, animals, fungi and other organisms that interact in specific ways that generate desired emergent properties.” In this study a Guild is defined as a set of species, including one species from each life form category, namely “tree”, “shrub” and non-woody and climbers”, promoting multiple ecological functions. Each life form has different strategies leading to complementary guilds. Meaning, that species composition within guilds enhances ecosystem functioning through resource partitioning, abiotic facilitation and biotic feedbacks (Barry et al., 2019).

To determine how guilds can promote multiple ecological functions, the functional trait-based approach can be used. This can deliver additional information for the design of guilds, as this approach focuses on the functional characteristics of a species instead of its taxonomic identity (de Bello et al., 2010). Nock et al. (2016) defined functional traits as the following: "Functional traits are morphological, biochemical, physiological, structural, phenological or behavioural characteristics of organisms that influence performance or fitness. Examples of functional traits are the following: Leaf area, wood density, plant height, dispersal capacity, leaf nitrogen content, diaspore mass, etc. (Lohbeck, 2014; Nock et al., 2016). There are inevitable trade-offs in plant form and function. State-

of-the-art research considers two main dimensions (Diaz, 2016). One explains the trajectory of short species tending to have small seeds to tall species tending to have large seeds. The second-dimension spans from species with cheaply constructed leaves to species with conservative leaves, translating to a longer leaf lifespan and higher survival when facing hazards. The study of functional traits can be used to link systems and targets to concrete design variables (e.g. species, temporal and spatial vegetation positioning and management practices) (van Eijk, 2021).

Therefore, the aim of this thesis was to compile and analyze functional traits of 70 selected plant species that are promising in Dutch food forest systems to gain insights into how species composition may promote ecological functions. Subsequently, the trait-based method was used to illustrate how complementary guilds can promote these ecological functions.

From the above, the following research questions logically follow:

To what extent can knowledge of functional traits inform decision-making in creating guilds providing multiple ecological functions?

To answer the main research question, corresponding sub-questions were formulated:

1. What are the synergies and trade-offs of functional traits on a species level?
2. In what way do functional traits link to specific ecological functions?

Methodology

Selection of ecological functions

Food forests have the potential to provide a wide range of ecological functions (Albrecht & Wiek, 2021). Ecological functions were selected through a literature review using google scholar and scopus. Potential functions that a food forest can provide were explored. The following functions were selected: carbon storage and sequestration, water regulation, soil fertility, erosion control and habitat provision.

Selection of functional traits

The Foundation ReGeneratie is involved and facilitates research, education and design/realization of food forests. In this context, they are setting up an Open-source food forest database where data from decades of practical experience and scientific research will be combined, covering plant properties and applications from ecology to economics (St. Regeneratie, 2023). More specifically, this database will contain information on 80 selected functional traits of 100 promising plant species, cultivars and rootstocks for food forest systems in the dutch context. Jordy van Eijk selected the species and functional traits during his master thesis. The selection was based on the most important functional targets, current and predicted future environmental conditions, successional gradients, ontogenetic variation, harvest practices and project scales (van Eijk, 2021).

This research analyzed eleven traits out of the eighty available in the database. This amount was selected to stay within this study's scope but have enough variability in the data. The selection of the traits was based on multiple aspects. They were based on how they link to the ecological functions that this study will assess, as well as, that the traits need to be obtained via a literature study.

The following traits were selected: relative growth rate, life span, height, crown diameter, nitrogen fixation, root pattern, soil moisture tolerance, natural occurrence, wind stress resistance, mineral accumulators, forest layer, crown density, root depth and leaf composition. Each trait needed to have no more than 30% missing data (for specific information on missing data, see Appendix 4. As insufficient data was available for crown density, rooting depth and leaf composition, they were discarded.

Figure 3 gives an overview of the links between functional traits and ecological functions that this study determined and used for further analysis. A detailed description of these links can be found in Appendix 1.

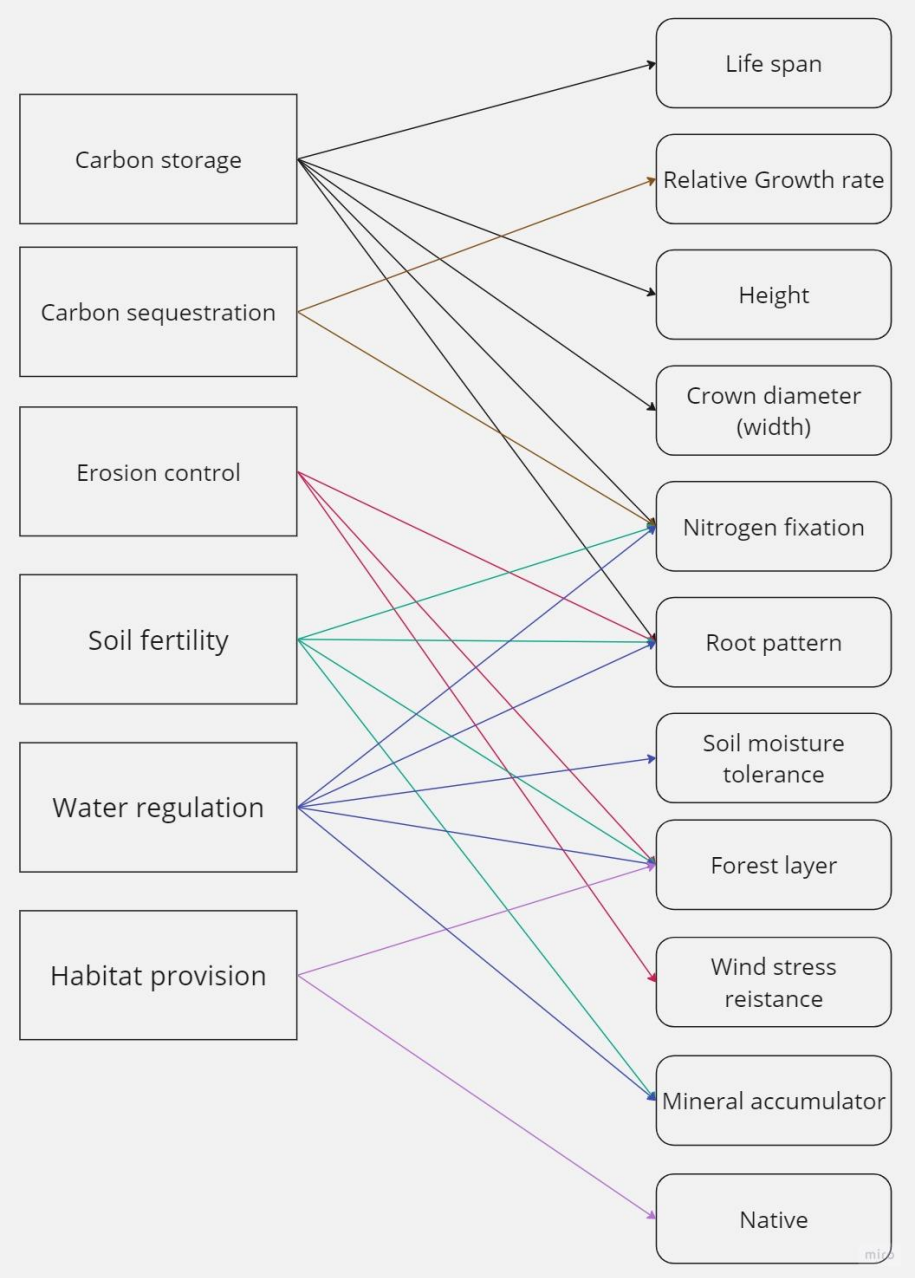

Figure 3: Links between ecological functions (column to the left) and functional traits (column to the right).

Species selection

This thesis planned to analyze 100 of the promising food forest species of the Database mentioned above. The species of the Database were chosen based on the 80 selected key functional plant characteristics and overall complementarity of inter-species variation. To guarantee the feasibility of this research, I stayed on the species level and did not include rootstocks and cultivars that are also represented in the Database. Lastly, a selection of these species was made based on the availability of trait data, resulting in a list of 70 species (see Appendix 3).

Data collection

After the functional traits had been selected, data on these traits of the promising food forest species was collected via literature research. Google scholar and scopus were used to obtain scientific literature. Additionally, sources were acquired from functional ecology databases like the TRY Plant Trait Database (Kattge et al., 2011) and the Syntropic Database created by Bitterlich Katharina during her Master thesis (Bitterlich, 2023). Further, the following published books were used to obtain data on functional traits: "Creating a forest garden", "Perennial Vegetables", "How to grow your own Nuts" and the second volume of "Edible Forest Gardens" (Crawford, 2010; Crawford, 2012; Crawford, 2016; Jacke & Toensmeier, 2005). Lastly, the Database of the tree nursery Ebben was used to obtain additional data (Boomkwekerij, 2023).

Data analysis

To analyze the data obtained in this thesis, a principal component Analysis (PCA) was performed using the FactoMineR package in the software R. As most traits were categorial Data, they had to be transformed in a certain way. If a trait had categories that could maintain an order, e.g. slow to fast, they were given values from low to high. Traits, with only two categories stating if a species had a particular trait or not, were made into binary dummy variables. Categories with no order in the ranking were split up into dummy variables as well. Missing data was imputed using the mice package. Then, the fviz_pca function was used to create graphs.

This information was then used to score each species based on how they promote certain functions. The score for carbon sequestration, erosion control and carbon storage were based on where the species were situated along the x-axis. The species on the most positive side was given 100% for carbon storage and 0% for carbon sequestration and erosion control, and the other way around. The score for soil fertility and water Regulation was based on the y-axis. The species on the most positive side was given 0% and at the most negative side 100%. Then guilds, consisting of 3 species, one from each life form, were created. The results of how these guilds score based on the ecological functions was then visualized in a nightingale chart.

Results

The results section is structured in the following way. Firstly, the results of the principal component analysis are presented. Then the link between the results of the PCA and the ecological functions is shown. Lastly, multifunctional guilds are presented.

The two-dimensional PCA biplot can be observed in Figure 4. This plot combines the graph of variables and individuals into one figure and shows synergies and trade-offs of functional traits on the species level. Firstly, the traits "forest layer", "width", "height", "lifespan" and "drought tolerance" (group 1) are positively correlated. Group 1 and relative growth rate are strongly negatively correlated. These traits are on opposing sides of the graph, close to dimension 1. This indicates that this dimension spans between these traits.

The second-dimension ranges from horizontal rooting pattern and belowground storage organ on one extreme and vertical and diagonal rooting pattern on the other. A high dependence on mineral accumulators and climbers can be observed as well. Climbers on top and mineral accumulators on the bottom.

Other logical conclusions that can be drawn are the following. A species is either drought tolerant or tolerant to wet conditions. Further, "wind stress resistance" and "vertical rooting pattern" point in the same direction, indicating a strong positive correlation. This indicates that species with a tap root are more resistant to winds. On the other hand, climbers and species with a horizontal rooting pattern have a low wind resistance, as these arrows are pointing towards the opposite of the arrow wind stress resistance. Also, it can be observed that the diagonal rooting pattern is not correlated with the other rooting patterns as its vector is approximately on 90 degrees to the other patterns. Lastly, nitrogen fixation is clearly not linked to life form. This can be explained by the fact that nitrogen fixers can be tree species, shrubs and non-woody species (Crawford, 2010).

The traits "forest layer", "rooting pattern", "width", "height", "lifespan" form a group with a comparably long vector, meaning that in these two dimensions they explain a large variation. On the other hand, "nitrogen fixation", "wetness tolerance" and "drought tolerance", are comparably small, meaning they explain little variation.

As mentioned above, the 70 species were classified into three life form categories: non-woody and climbers, trees and shrubs. It is important to note that the category of non-woody and climbers is quite diverse and consists of herbs, perennial vegetables and climbers. Woody species are situated more towards the right of the graph, and non-woody species are more towards the left. It can be seen very clearly that trees are on the right and non-woody species on the left. While bushes build a category that is somehow in between. This could be explained by the fact that this category spans from very tall shrubs that would be categorized as the canopy layer till low shrubs.

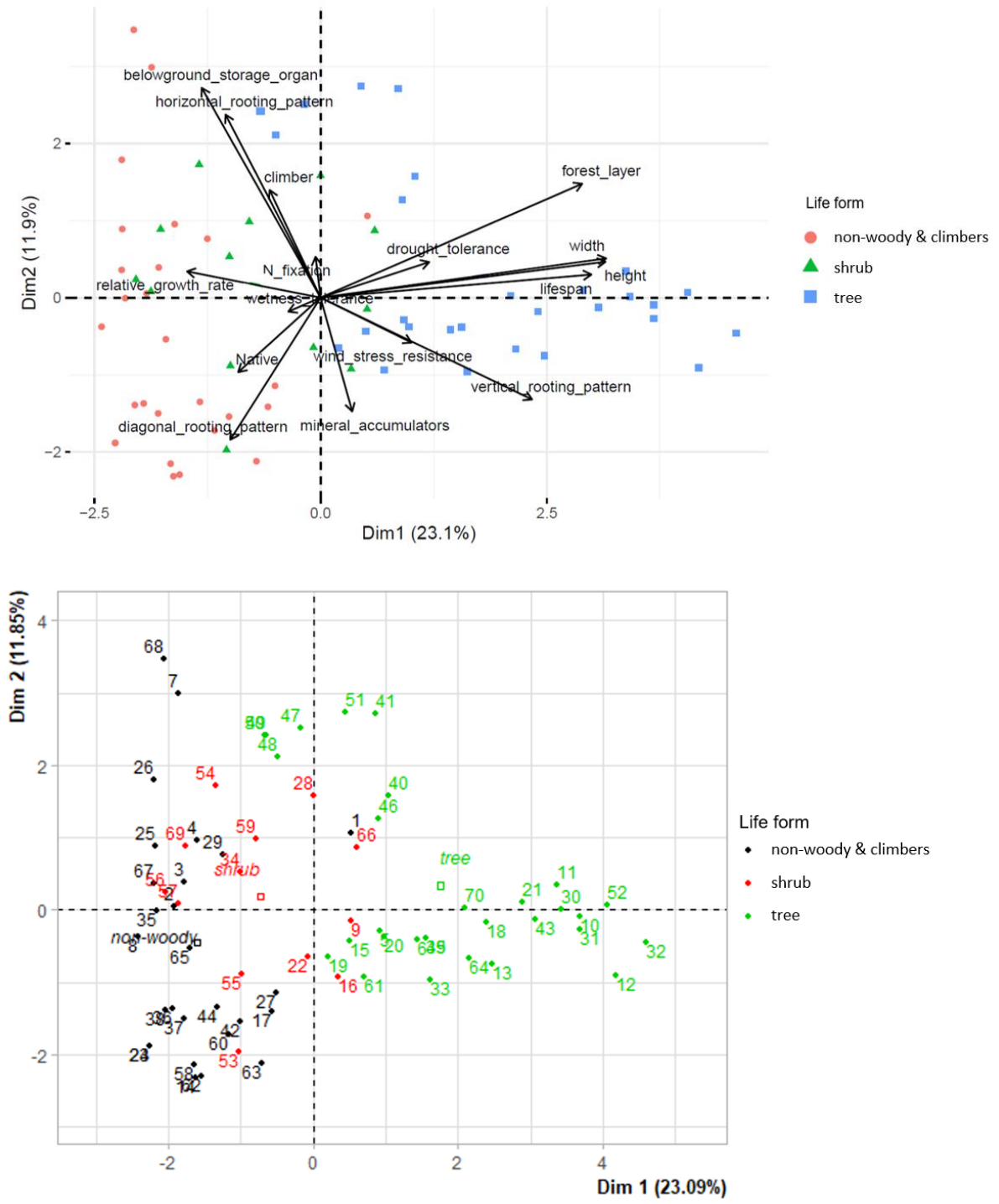

Figure 4: PCA biplot separating species based on their functional traits (top). PCA graph of individuals, including species numbers (bottom). Both graphs are colour coded by the life forms. Life form non-woody and climbers consisting of herbs, perennial vegetables and climbers.

Linking functional traits and ecological function with results of PCA

The ecological functions have been placed on the corresponding sections in the PCA graph of variables (Figure 5). This means, species situated in the sections where the ecological function is placed are important to promote this function.

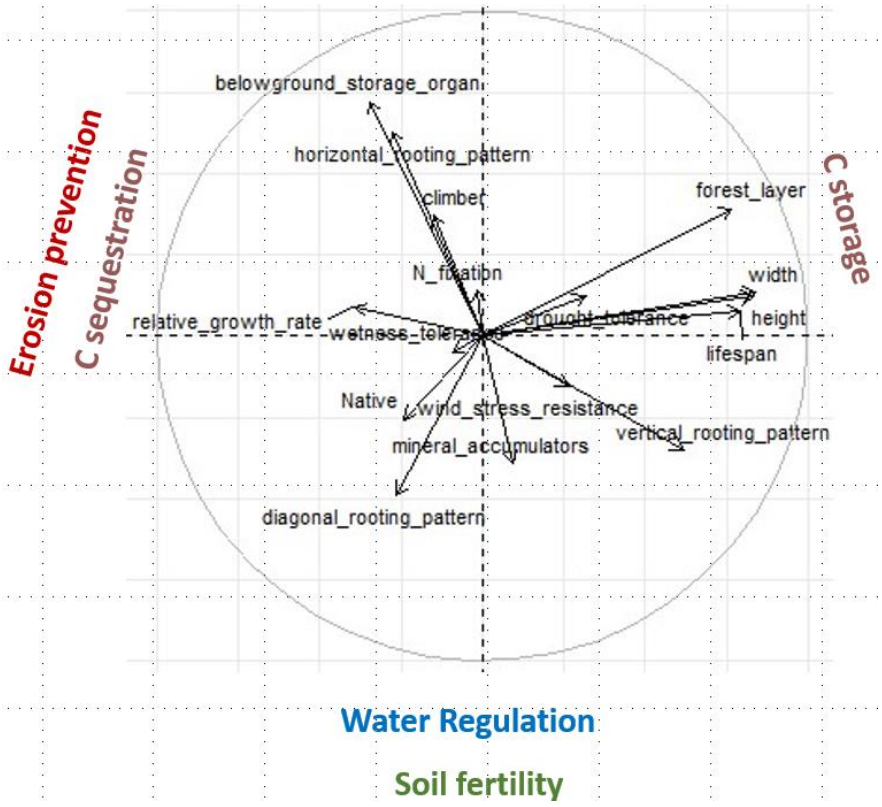

Figure 5: Ecological functions on corresponding sections in the PCA Graph

As mentioned above "nitrogen fixation", "wetness tolerance" and "drought tolerance", are comparably small, meaning that it is not strongly related to variation in traits that do explain the variation. Therefore, they have not been considered while placing the functions on the graph. Further, habitat provision was linked to the trait forest layer based on functional complementarity, meaning that a combined range of categories is beneficial. This link was not considered in Figure 5, as this means a trade-off at species level. Therefore, the ecological function habitat provision is not indicated in Figure 5.

Trade-offs and overlaps between functions can be observed in Figure 5. Water regulation and soil fertility (group 1) are provided by the same set of species — the same counts for erosion prevention and carbon sequestration (group 2). Carbon storage does not show any overlap with other functions. Lastly, carbon storage and group 2 oppose each other, suggesting that very different species provide these functions. Summarizing it can be said that the ecological functions are distributed over the graph in 3 distinct groups.

Multifunctional guilds

The graph of individuals for the PCA of Figure 4, combined with the knowledge gained by linking functional traits and ecological functions in Figure 5, was used to score species based on the extent to which they promote specific ecological functions. To illustrate, four guilds were created, 3 that are not that different in functional traits, and one that exhibits optimal functional complementarity.

This analysis was done on a subset of species, namely, 70. Of these 70 species, 30 are trees, 13 are shrubs, and 27 are non-woody and climbers. This results in 10530 possible guild formations if one species per life form is chosen for a guild. More combinations can be made for guilds that include more species. Figure 6 gives an overview of where the species chosen for each guild are situated within the PCA.

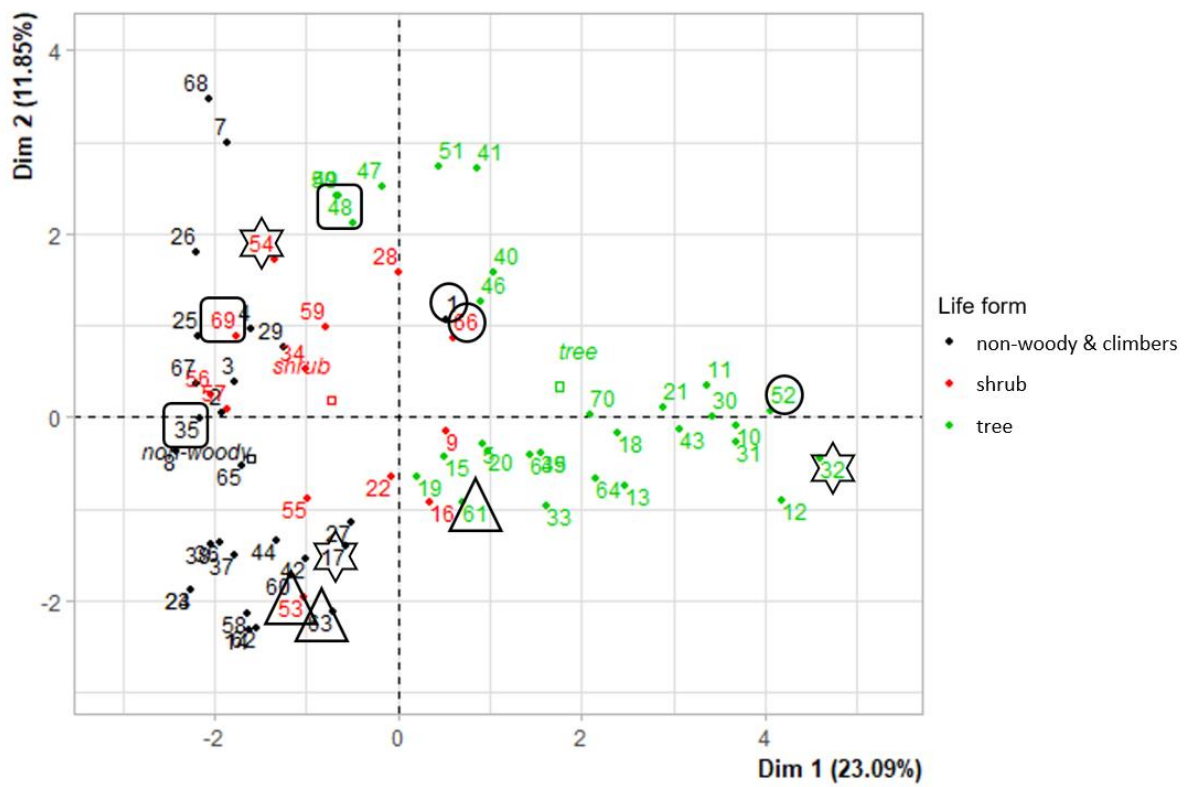

Figure 6: Species chosen for the guilds highlighted in PCA graph of individuals. Guild 1 indicated by circles, guild 2 by squares, guild 3 by triangles and guild 4 by stars

Table 1 gives an overview of the species composition of each guild and how these species scored individually and combined. The scaled sum of the scores for each ecological function per guild is visualized in Figure 7, 8, 9 and 10.

Table 1: Species composition and scores for ecological functions of Guilds. In the following order from top to bottom: 1,2,3,4

Nr	Species	Life form	C storage [%]	Erosion control C sequestration [%]	Water Regulation Soil fertility [%]
1	Actinidia arguta	non-woody	42	58	42
52	Quercus ilex	tree	92	8	59
66	Vaccinium corymbosum	shrub	43	57	45
	sum		177	123	145
	sum scaled		59	41	48
Nr	**Species**	**Life form**	**C storage [%]**	**Erosion control C sequestration [%]**	**Water Regulation Soil fertility [%]**
35	Malva moschata	non-woody	4	96	60
48	Prunus domestica	tree	27	73	23
69	Zanthoxylum piperitum	shrub	9	91	45
	sum		41	259	128
	sum scaled		14	86	43

Nr	Species	Life form	C storage [%]	Erosion control C sequestration [%]	Water Regulation Soil fertility [%]
63	Taraxacum officinale	non-woody	24	76	97
61	Sorbus domestica	tree	44	56	76
53	Ribes nigrum	shrub	20	80	94
	sum		89	211	267
	sum scaled		30	70	89

Nr	Species	Life form	C storage [%]	Erosion control C sequestration [%]	Water Regulation Soil fertility [%]
17	Crambe maritima	non-woody	26	74	84
32	Juglans nigra	tree	100	0	68
54	Ribes uva-crispa	shrub	15	85	30
	sum		142	158	182
	sum scaled		47	53	61

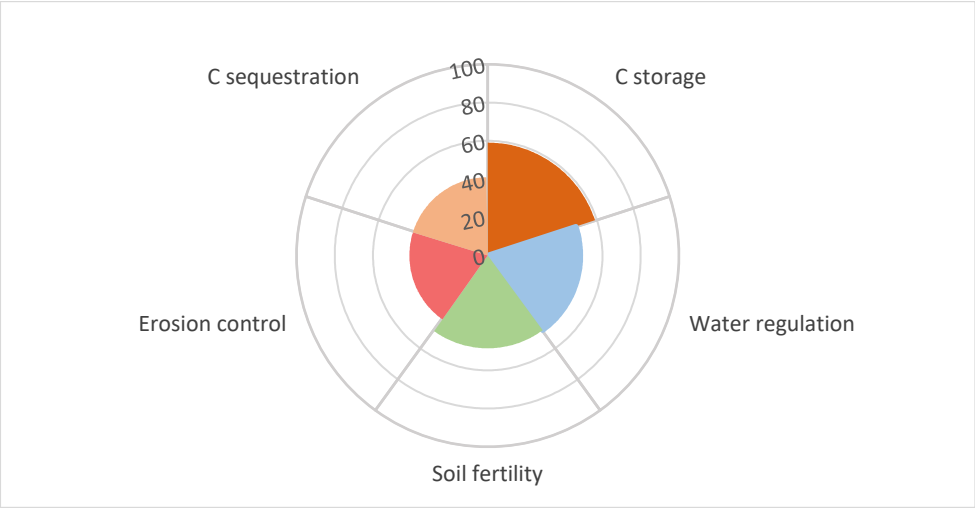

Figure 7: Ecological functions promoted by guild 1

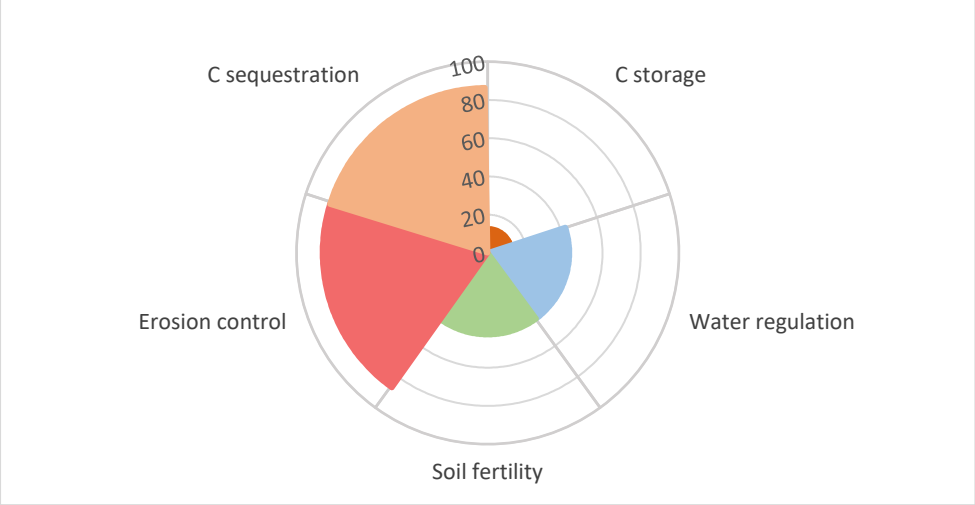

Figure 8: Ecological functions promoted by guild 2

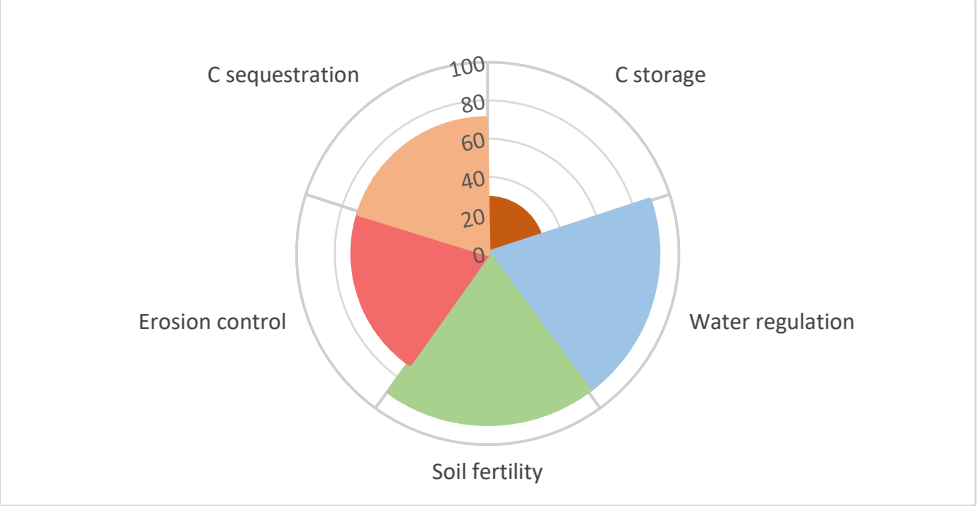

Figure 9: Ecological functions promoted by guild 3

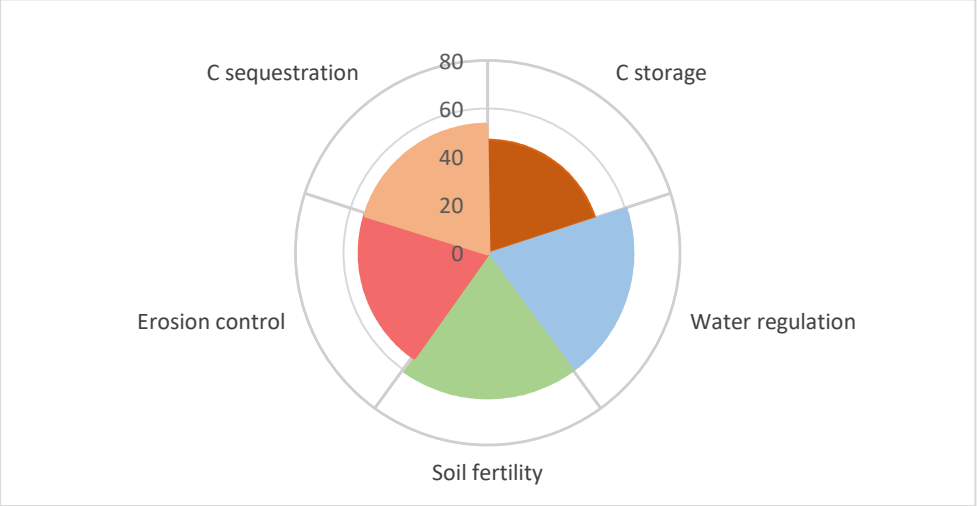

Figure 10: Ecological functions promoted by guild 4

The charts show that depending on the specie chosen, there is a clear difference in how a guild promotes each ecological function. It can be observed that guild 1 and 4 more evenly spread throughout the ecological functions. However, guild 4 has significantly higher values than guild 1. Species of guild 1 are situated towards the upper right of the PCA, indicating that they promote carbon storage. This can also clearly be observed in Figure 7, even though the ecological functions are quite evenly spread out, carbon storage is highest. Guild 2 clearly promotes carbon sequestration and erosion control most, while the other functions are promoted significantly less. The same counts for guild 3, however, here water regulation and soil fertility are promoted most.

Carbon sequestration and erosion control, as well as, water regulation and soil fertility are promoted by species that are located at the same place in the graph. Therefore, if one of these function is promoted, the other function is promoted as well, leading to a higher benefit in total.

Discussion

The results of this study provided insight into how knowledge of trait strategies and trade-offs can inform the design of guilds, which provide multiple ecological functions. In the following sections of this chapter interpretations, implications and limitations of these findings will be discussed. Lastly, recommendations for future research will be provided.

Fourteen functional traits were selected for analysis at the start of this research project. Three of them had to be disregarded because not enough data could be obtained. Then, the trait wind stress resistance, identified at first, was not used for the analysis as it turned out the benefit of a wind stress resistant plant is more in providing wind shelter in wind breaks for other plants. Windbreaks can mitigate evapotranspiration (Cochrane & Vries, 2014) and reduce wind erosion (TECA, n.d.). Wind stress resistance can be beneficial, however, there was no identified link on how it can enhance the identified ecological functions on a species level.

The traits nitrogen fixation and soil moisture tolerance were indicated by small arrows in the PCA graph. The fact that they are not strong indicates that they are not strongly related to variation compared to the traits that explain much variation. As this data is multidimensional, it is possible that in a third dimension, which is not visible in the two-dimensional graph, they are strong indeed. It is just not possible to deduct this from this two-dimensional PCA graph.

One outlier was identified in the PCA, a climber that performs more than the category tree. One explanation could be that climbers were classified as the highest forest layer. Possibly, in all other characteristics, it performs as non-woody and climbers but because of the forest layer it was pulled towards the upper right.

Analysis of the PCA has shown that dimension one spans between the evolutionary trade-off growth and survival, which means species with acquisitive strategies investing in a fast growth rate at the cost of lower survival versus species with conservative strategies investing in survival under harsh conditions. This is consistent with literature of functional trait strategies (Diaz et al, 2006).

The second-dimension ranges from horizontal rooting pattern and belowground storage organ on one extreme and vertical and diagonal rooting pattern on the other. Each rooting pattern can be found on distinct places within the PCA, indicating functional complementarity if species from different rooting patterns are combined. Jacke & Toensmeier (2005) indicated, that despite a lack of information on root system complementarity, mixing plants with different root pattern leads to a fuller use of the soil profile and therefore can potentially enhance complementarity. Their statements are in line with the findings of this research.

To create guilds providing multiple functions, it was important to know how ecological functions and functional traits relate to each other. The ecological function habitat provision relied on the functional trait forest layer. This link is based on functional complementarity. This is since multiple, interconnected layers of vegetation diversify wildlife habitat (van Eijk, 2021). Therefore, this function was not placed on the PCA graph of functions. However, it can be argued that this function is promoted by forming guilds consisting of different life forms and species.

The other ecological functions could be placed in distinct places within the PCA graph of functions. Here, synergies and trade-offs between the functions could be observed. Unsurprisingly, there was a trade-off between the function of carbon sequestration and carbon storage. As mentioned above, the first dimension of the PCA spans between growth and survival. Therefore, carbon storage can be associated with species having conservative strategies, while carbon sequestration with species that have acquisitive strategies. This is consistent with existing literature (van Eijk, 2021). The overlap between the functions of water regulation and soil fertility were unexpected. Their overlap can be attributed to the fact that within the range of traits observed in this study, similar traits had a positive influence. However, if more data were considered, maybe a more prominent differentiation could be observed. The functions of carbon sequestration and erosion control, which were linked to different functional traits, were also positioned in the same place on the plot. This could be because plants associated with a high growth rate, promoting carbon sequestration, have traits that positively influence erosion control. There was no evidence found in literature to back up this statement. However, this could be further explored.

It needs to be considered that species were scored in a simple manner, the closer a species is situated to the part of the PCA graph where a certain ecological function was placed, the higher the score. This was done to be able to create illustrative multifunctional guilds, which enabled observations on how more functional different versus functional similar species promote ecological functions. However, there is more nuance to how much a species contributes towards a certain function. This needs to be considered when looking at the results of this study. However, this simple scoring system enabled to explore how the knowledge of functional traits can lead to enhanced ecological functioning. Guilds that were created showed different results in how they promote multiple ecological functions. It could be observed that guild 1 and 4 were more evenly spread throughout the ecological functions. However, guild 4 had significantly higher values than guild 1. This could be due to the fact that guild 4 is functionally more different, leading to functional complementarity, which could potentially increase ecological functioning. Guild 2 and 3, were both leaning towards some functions, while promoting others significantly less. This can also potentially be attributed towards the fact that, even though consisting of 3 different life forms, each species is functionally similar. Guild 2, clearly promoting carbon sequestration and erosion control most, promoted carbon storage the least. This was expected due to the fact of the inevitable trade-off between carbon storage and sequestration. Therefore, the total sum of these two groups is always 100% combined, meaning that if one scores high, the other scores lower.

This analysis was done on a subset of 70 species within three categories. This led to 10530 possible guild combinations. This was just a subset and there are many more promising species for food forestry in the Netherlands and in different countries and climatic zones. Therefore, there are many possibilities on how species could be combined. The methodology explored in this study could be applied to different species and contexts, guiding how species could be chosen and integrated into food forestry.

Limitations and Future Research

This study had to face certain limitations throughout the research. These will be explored here. Further, recommendations for future research will be given.

The selection of functional traits was based on the connections identified through a review of the existing literature, although a more in-depth analysis could be conducted. Further research is needed to explore all the positive and negative connections, as well as indirect effects between functional

traits and ecological functions, maximizing the potential implications of this approach for future research.

The availability of specific data on functional traits required for this study was limited. As a result, next to scientific databases, data was also obtained from books written by practitioners in the field of food forestry, which, however, may not adhere strictly to scientific standards.

The classification of the trait "relative growth rate" into slow, medium, and fast is highly subjective and influenced by factors such as climate and resource availability (Jacke & Toensmeier, 2005). This leads to uncertainties associated with this trait. Future research should aim to address these uncertainties and explore the influence of climate and resource factors.

The trait root pattern and its classification were based on the Food Forest Database. However, there are various classification systems to categorize root patterns. Due to the complexity and variability of root systems, this categorization remains an ongoing and evolving field of study. Currently, there are several different terminologies and categories, with often unclear interpretations, making it a vague construct. It could be argued that it is not possible to categorize a root pattern, but more optimal to use several root traits to describe rooting systems of plants. Therefore, it would have been optimal to have root traits such as rooting depth, root mass, rooting density and root diameter (Bakker, 2018). However, this data was simply unavailable, so the rooting patterns were used as a proxy. Another aspect of root systems is that despite limited research on root-system complementarity, it is likely that mixing plants with different root pattern types results in a fuller use of the soil profile, leading to more soil stability (Jacke & Toensmeir, 2005). Future research is necessary to gather comprehensive root trait data to enhance knowledge of the unexplored world of roots.

Due to the unavailability of data and time limitations, not all functional trait data could be obtained. Therefore, missing data was imputed by the mice Package in R. This could potentially result in a distorted result.

Further, as mentioned above, several traits could not be included in the analysis for various reasons. However, they could potentially be essential for specific functions. Also, species got put into categories. However, how they function within this category can still be different. For example, non-woody species can provide soil erosion through ground cover very differently. While some may be very effective, others may not. This should be considered when assessing the results of this research.

The methodology to score the species for an ecological function was done in a simple manner.
Other, more complex, but therefore more precise ways should be assessed by future research.
However, what speaks for this methodology is its fast and easy replicability, giving a general trend.

The functional trait approach is promising in determining the design of food forest guilds. However, many traits needed for this analysis are not available. For example, rooting depth and mineral accumulators need to be explored further. In addition, there is a need for monitoring ecological functions in actual food forests to be able to establish the link between species and functionality, as well as, between guilds and functionality more directly. Therefore, more field and lab research are crucial to provide the necessary data for the design of food forests.

Conclusion

The aim of this thesis was to compile and analyze functional traits of 70 selected plant species that are promising in dutch food forest systems to gain insights into how species composition may promote ecological functions. The central research question was: To what extent can knowledge of functional traits inform decision-making in creating guilds providing multiple ecological functions?

To answer this question, several functional traits and their associations with the ecological functions carbon storage and sequestration, water regulation, soil fertility, habitat provision and erosion control were identified and analyzed. A principal component analysis was conducted to observe synergies and trade-offs at species level. This information was used to create a visual overview on how species differ in their ability to support different ecological functions. It revealed an overlap between the ecological functions soil fertility and water regulation, as well as, between erosion control and carbon sequestration, meaning that species that provides one function also provide the other. Further, an inevitable trade-off between carbon sequestration and carbon storage was identified.

Three guilds that are not that different in functional traits yet represent 3 life forms and one that exhibits optimal functional complementarity were created to illustrate how species composition can lead to distinct outcomes in ecological functioning. It can be concluded that within a guild that represents different life forms, there can still be a range of functional complementarity, which has consequences for multifunctionality. Therefore, the functional trait approach can give additional information for the design of guilds. Meaning that species are not only selected based on different life forms, but also based on the functional complementarity which can lead to enhanced ecological functioning.

The methodology presented here can be extended to other species, functional traits, and ecological functions, facilitating the exploration and application of similar concepts in diverse contexts. However, to further enhance the applicability of this approach, future studies should focus on obtaining more trait data and explore the diverse connections between these traits and the benefits they can be linked to. Alternative food systems are needed to produce environmentally friendly and healthy food for the wider community. This approach can be one step in assessing and designing such systems.

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Appendix

Appendix 1: Ecological functions and how they are linked to functional traits

Water regulation

Climate change has led to an increase in the occurrence and intensity of extreme weather (Stott, 2016). This increasing frequency poses a significant threat to agriculture (Cogate, 2019). Droughts, on one hand, and excessive rainfall, on the other, can both have detrimental effects. Here I explore how plants can enhance water regulation.

Runoff results from an exceedance in infiltration rates, which is likely to happen during heavy rainfalls. This runoff is not only a loss of nutrients (see chapter soil fertility) but also a loss of water that could have contributed towards crop production and groundwater supplies (n.a., 2021). Water infiltration is impacted by soil stability, making it an important aspect of water regulation (Ali et al., 2017). Vegetation can play a role in creating more soil stability due to various processes. Firstly, a dense root network can bind soil particles by excreting root exudates (Ali et al., 2017). Plant species that form a denser root network usually have a fibrous root system (Gyssels et al., 2005). Secondly, dense aboveground vegetation has the ability to protect soil from structural breakdown under wind and rain (Ali et al., 2017). In tree cropping systems, ground cover management is an important strategy to create this dense vegetation layer (Liu et al., 2021).

Another important aspect is soil compaction. It reduces infiltration, water storage and drainage and can therefore lead to excessive runoff (Raper & Kirby, 2006). To combat this issue plants with deep, strong taproots can be used to penetrate and loosen the soil (Hamza & Anderson, 2005).

A higher occurrence of drought can also be observed in the Netherlands (Boesveld, 2021). Drought-tolerant plants have developed various adaptations and features to help them minimize water loss and maximize water uptake (Wilson, 2014). The use of these plants can therefore be beneficial. Further, as discussed earlier, as extreme weather increases, heavy rainfalls can be an additional problem if infiltration rates are exceeded. Therefore, a mix of drought-tolerant plants and plants tolerating wet conditions can lead to more stability (van Eijk, 2021).

Reducing wind speed through windbreaks can mitigate evapotranspiration. Therefore, including plants that can withstand wind can be beneficial to decrease water loss (Cochrane & Vries, 2014).

Lastly, Nitrogen fixing plants produce high N containing litter and mineral accumulators bring nutrients to the surface, which can enhance primary productivity and carbon input at the community level (De Deyn et al., 2008). This can lead to an increase in organic matter, which increases the water holding capacity of the soil (Lal, 2020).

Erosion control

Soil erosion is a process in which the impact of water or wind removes soil particles (Al-Kaisi, 2023), reducing available water, nutrients, and Organic matter (Pimentel et al., 1987). It is, therefore, an important environmental issue threatening world food production (Pimentel et al., 1987). To combat this issue, Guilds should be designed to reduce erosion as much as possible. Several functional traits can be associated with erosion control, some of which will be discussed in the following paragraphs.

Soil stability is an important aspect in erosion control (Ali et al., 2017). As discussed in the chapter Water Regulation, vegetation impacts soil stability in several ways. These same aspects can be applied here to increase soil stability and reduce erosion.

Further, as discussed in the chapter water regulation, soil compaction reduces infiltration, water storage and drainage and can lead to excessive runoff and erosion (Raper & Kirby, 2006). To combat this issue plants with deep, strong taproots can be used to penetrate and loosen the soil (Hamza & Anderson, 2005). However, the effectiveness of Erosion control increases exponentially with increasing soil surface occupied by fine roots. This effect is even stronger in the case of lateral roots because these roots form an important network that strengthens cohesion of soil (Gyssels et al., 2005)

Wind has erosive power (TECA, n.d.). Windbreaks can prevent wind erosion for 10 to 20 times their height downwind and filter wind-blown soil particles from the air (Kuhns, 1998). Therefore including plants that can withstand wind and act as a windbreak can be beneficial to decrease erosion (TECA, n.d.).

Soil fertility

Soil fertility refers to the capacity of soil to support the growth of plants by supplying necessary nutrients, creating favourable chemical and physical conditions, and offering a suitable environment for plant development. It is, therefore, crucial for agricultural productivity and food security (fao, 2023).

Ground cover management significantly reduces nitrogen and phosphorus losses in runoff. Therefore, Ground cover vegetation is essential for maintaining soil fertility (Liu et al., 2021).

As crops and fruits are harvested, Nitrogen is removed from the system. Therefore, additional Nitrogen is needed for continuous growth and soil fertility. Industrial agriculture is making use of fertilizers. This, however, leads to various adverse effects. An alternative for improving Nitrogen in the soil is Nitrogen fixing plants (Ganry, n.d.).

There has been limited research conducted on dynamic accumulators. However, there has been increasing interest in their potential as nutrient-catch crops, nutrient-rich mulches and liquid fertilizers. Accumulators are plants that extract a particular mineral from the soil and accumulate it in their aboveground parts. (Tyler & Zarro, 2021). Due to this, they can minimize leaching losses and bring nutrients to the surface (Jacke & Toensmeier, 2005).

Soil compaction enhances soil strength and decreases soil fertility by reducing water and nutrient storage and availability. This leads to an increased demand for nutrient inputs. As discussed in the chapter water regulation, plants with deep, strong taproots can be used to combat this issue (Hamza & Anderson, 2005).

Carbon storage and sequestration

An increase in global consumption of fossil fuels has led to a rise in the concentration of atmospheric CO2 levels, leading to several detrimental effects (Lindsey, 2023). In hindsight of this, future agricultural systems should not be an additional driver of this problem, but on the other hand, be able to adapt and mitigate it. An important aspect is carbon sequestration and storage in vegetation and soil. The following paragraphs will discuss several functional traits enhancing C storage and sequestration.

The functional trait lifespan plays an important role in Carbon storage as they allocate a higher amount of Carbon into physical support structures, leading to tough and dense litter forms, which are slow-cycling and therefore support long-term carbon storage (De Deyn et al., 2008). Further, a high tree volume (height, crown diameter, root depth) results in larger structures containing Carbon, resulting in a larger Carbon pool stored in vegetation (van Eijk, 2021). On the other hand, netto

sequestration is increased by a fast growth rate, as this means a fast accumulation of biomass where Carbon can be captured (van Eijk, 2023; de Bello et al., 2010).

Continuing with the influence of roots on carbon storage, two strategies in rooting pattern can be observed. Fine roots that decompose fast and thick roots that decompose over a long period. Literature suggests that if there is a higher diversity in plants, total root biomass is higher, leading to more Carbon stored in the root system. (van Eijk, 2021)

Nitrogen fixing plants produce high N-containing litter, which can enhance primary productivity and carbon input at the community level (De Deyn et al., 2008). Further, fertilizers contribute significantly to the carbon footprint in agriculture (Brentrup et al., 2016). Using Nitrogen fixing plants leads to less dependency on these fertilizers and can therefore reduce carbon emissions.

Another aspect is soil compaction. Compacted soils have less ability to store Carbon than lose soils with stable aggregates (Brevik et al., 2002). As discussed in the chapter water regulation, plants with deep taproots can help to combat this issue.

Habitat provision

The Netherlands is a highly populated country with few natural protected areas. Habitat fragmentation for wildlife is an issue (Sanders, 2019). Food forests have the ability to provide habitat for wildlife and create corridors throughout the landscape (van Eck, 2023).

By creating multiple, interconnected vertical layers of vegetation, wildlife habitat can be diversified. Further, the movement of species between forest layers is encouraged. Especially climbers can be beneficial in connecting different layers throughout the food forest (van Eijk, 2021).

Another aspect is naturally occurring plant species. Research has shown that how long a species has been present in an area plays an important role in providing habitat for insects. As an example a willow tree provides habitat for around 450 species, while the Walnut only 2 (Kennedy & Southwood, 1984). Further, bird habitat also improves with the usage of native species due to the fact that non-native plants do not support sufficient prey resources, foraging substrates or breeding locations for insectivorous birds. In summary, preserving native plants is a good strategy for improving landscapes for wildlife habitat (Narango et al., 2017).

Relative growth rate

The relative growth rate can be defined as the rate at which a plant grows in terms of its increase in size or biomass per unit of time relative to its initial size (van Eijk, 2023). It was classified into the categories slow, medium and fast.

Lifespan

The Lifespan is defined as the length of time a plant species can survive and reproduce under favourable environmental conditions (van Eijk, 2023). The classification was made in the following manner: very short:<1y; short: annual; medium:2-10y long:10-20y very long:>20y.

Height

Height is defined as the maximum vertical height that a plant species can reach at maturity (van Eijk, 2023). Sources of this trait would indicate a range. For the statistical analysis the average between these range was taken as the final value.

Crown diameter (width)

The Crown diameter, also expressed as with, is defined as the distance across the widest part of a plant's foliage or branches in the upper portion of the plant (van Eijk, 2023). Sources of this trait also indicated a range. Therefore, an average was taken again.

Soil moisture tolerance

Soil moisture tolerance is the range of soil moisture levels that a particular plant can withstand without experiencing adverse effects on its survival (van Eijk, 2023). This trait was classified in the categories: wet, moist, dry and drought.

Nitrogen fixation

The trait Nitrogen fixation simply describes whether the plant can fix Nitrogen or not.

Natural occurrence

Natural occurrence is defined as the following: a plant species that occurs and grows naturally in its native habitat without human intervention (van Eijk, 2023). Here, plants that are native to Europe were classified as Native.

Wind stress resistance

Wind stress resistance describes the ability of a particular plant species to withstand and recover from physical damage caused by wind, including bending, breaking, or uprooting (van Eijk, 2023). It was classified into the categories: "not tolerant", "slightly tolerant" and "tolerant".

Forest layer

The trait forest layer is the forest layer occupied when the plant reaches its maximum height (van Eijk, 2023). The categories are the following: "Ground cover" = herbs and grasses, "low shrub" = shrubs below 2.5m, "low tree/large shrub" = trees and shrubs below 6, and "canopy" = trees and shrubs above 6m.

Dynamic accumulator

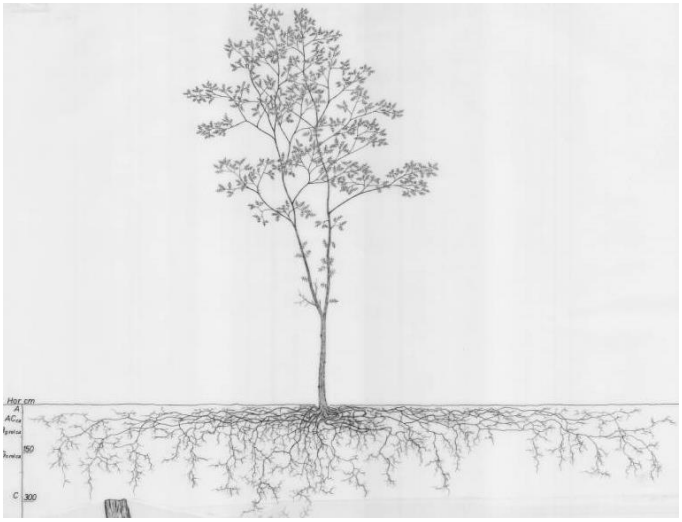
Accumulators can be defined as plants that extract a particular mineral from the soil and accumulate it in their aboveground parts (Tyler & Zarro, 2021). This study made a classification based on whether there was evidence that a plant is a dynamic accumulator or not.

Root pattern

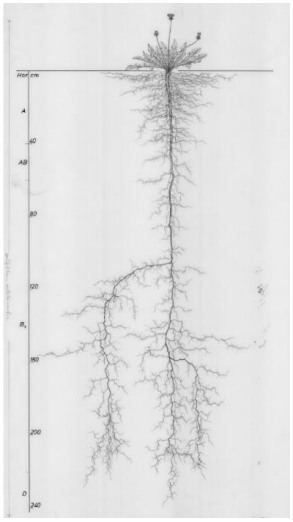
The Root pattern can be described as the arrangement of a plant's roots in the soil. Researchers have developed various classification systems to categorize rooting patterns based on specific criteria, such as the depth of roots, the extent of lateral spreading, or the presence of taproots. However, due to the complexity and variability of root systems, categorization remains an ongoing and evolving field of study. As Data was obtained for the Food forest Database with a different classification, namely, fibrous roots, heart roots, rhizomatous roots, tap roots and tubers and bulbs, this categories were used and translated into the categories used in this research. Appendix Table 1 describes the translation of categories. This study categorized the rooting pattern into 3 categories: "vertical", "horizontal" and "diagonal". This describes the directional growing behaviour of roots, an example of each category can be observed in appendix Figure 1, 2, 3. A fourth category is described as the Belowground storage organ (see appendix Figure 4).

Root pattern current study	Root pattern Food Forest Database
Horizontal root pattern	Flat, rhizomatous
Diagonal root pattern	Heart root, fibrous root
Vertical root pattern	Tap root
Belowground storage organ	Bulbs, tubers

appendix Table 1: Root pattern classification

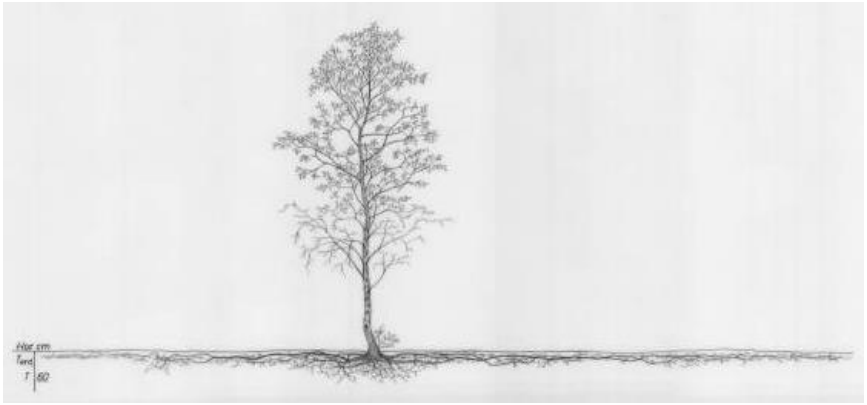


appendix Figure 1 Diagonal root pattern. Species Sorbus Domestica (WUR, 2023)



appendix Figure 2: Vertical root pattern. Species Taraxum officinale (WUR, 2023)

:



appendix Figure 3: Horizontal root patter. Species Betula pendula (WUR, 2023)

appendix Figure 4: Belowground storage Organ (Ohyama et al., 2006)

Appendix 3: List of selected promising food forest species and corresponding numbers

Nr	Species
1	Actinidia arguta
2	Allium ampeloprasum
3	Allium fistulosum
4	Allium tuberosum
5	Alnus cordata
6	Amelanchier alnifolia
7	Apios americana
8	Brassica oleracea
9	Caragana arborescens
10	Carya illinoinensis
11	Carya laciniosa
12	Carya ovata
13	Castanea mollissima
14	Chenopodium bonus henricus
15	Cornus mas
16	Corylus avellana
17	Crambe maritima
18	Crataegus pinnatifida
19	Cydonia oblonga
20	Diospyros kaki
21	Diospyros virginiana
22	Elaeagnus multiflora
23	Fragaria moschata
24	Fragaria vesca
25	Helianthus tuberosus
26	Hemerocallis lilioasphodelus
27	Heracleum sphondylium
28	Hippophae rhamnoides

29	Humulus lupulus
30	Juglans ailantifolia
31	Juglans cinerea
32	Juglans nigra
33	Juglans regia
34	Lonicera caerulea
35	Malva moschata
36	Matteuccia struthiopteris
37	Melissa officinalis
38	Mentha suaveolens
39	Mespilus germanica
40	Morus alba
41	Morus nigra
42	Myrrhis odorata
43	Pinus koraiensis
44	Polygonatum biflorum
45	Prunus armeniaca
46	Prunus avium
47	Prunus cerasifera
48	Prunus domestica
49	Prunus dulcis
50	prunus persica
51	Pyrus communis
52	Quercus ilex
53	Ribes nigrum
54	Ribes uva-crispa
55	Rosa rugosa
56	Rubus fruticosus
57	Rubus idaeus
58	Rumex acetosa
59	Sambucus canadensis
60	Scorzonera hispanica
61	Sorbus domestica
62	Symphytum officinale
63	Taraxacum officinale
64	Toona sinensis
65	Urtica dioica
66	Vaccinium corymbosum
67	Viola odorata
68	Vitis vinifera
69	Zanthoxylum piperitum
70	Ziziphus jujube

Appendix 4: selected functional traits, their sources, and missing Data

Selected functional trait	Source	Missing Data
Life span	Kattge et al., 2011; Crawford, 2010; Crawford, 2016	**20/70**
Relative Growth Rate	Jacke & Toensmeier, 2005; Bitterlich, 2023; Crawford, 2010	2/70
Height	Jacke & Toensmeier, 2005; Crawford, 2010; Bitterlich, 2023; Boomkwekerij, 2023	0/70
Crown diameter (width)	Jacke & Toensmeier, 2005; Crawford, 2010; Bitterlich, 2023; Boomkwekerij, 2023; Kattge et al., 2011	0/70
Nitrogen fixation	Jacke & Toensmeier, 2005	0/70
Root pattern	Jacke & Toensmeier, 2005; Crawford, 2010; Bitterlich, 2023	**20/70**
Soil moisture tolerance	Jacke & Toensmeier, 2005; Crawford, 2020; Crawford, 2010	0/70
Forest layer	Jacke & Toensmeier, 2005; Crawford, 2020; Crawford, 2010	0/70
Wind stress resistance	Boomkwekerij, 2023; Crawford, 2020; Crawford, 2010; PFAF, 2023; Crawford, 2016; Jacke & Toensmeier, 2005;	**20/70**
Mineral accumulator	Jacke & Toensmeier, 2005	0/70
Native	Jacke & Toensmeier, 2005; Crawford, 2020	0/70

Appendix 5:Species scores for ecological functions

Nr	life form	X	Y	C storage [%}	C seqestration & Erosion control	Water Regulation & Soil fertility
1	non-woody	1.4	3.0	42	58	42
2	non-woody	-5.5	0.2	7	93	59
3	non-woody	-5.1	1.1	9	91	53
4	non-woody	-4.6	2.7	12	88	43
5	tree	2.6	-0.9	48	52	65
6	tree	4.0	-1.2	55	45	67
7	non-woody	-5.3	8.5	8	92	8
8	non-woody	-6.9	-1.0	0	100	66
9	shrub	1.4	-0.4	42	58	63
10	tree	10.4	-0.3	87	13	62

11	tree	9.5	1.0	82	18	54
12	tree	11.8	-2.6	94	6	76
13	tree	6.9	-2.1	70	30	73
14	non-woody	-4.6	-6.6	12	88	100
15	tree	1.4	-1.2	42	58	67
16	shrub	0.9	-2.6	39	61	76
17	non-woody	-1.7	-4.0	26	74	84
18	tree	6.7	-0.5	69	31	63
19	tree	0.5	-1.8	37	63	71
20	tree	2.7	-1.0	48	52	66
21	tree	8.1	0.3	76	24	58
22	shrub	-0.3	-1.9	33	67	71
23	non-woody	-6.5	-5.3	2	98	93
24	non-woody	-6.5	-5.3	2	98	93
25	non-woody	-6.3	2.5	3	97	45
26	non-woody	-6.3	5.1	3	97	29
27	non-woody	-1.5	-3.3	27	73	80
28	shrub	-0.1	4.4	35	65	33
29	non-woody	-3.6	2.2	17	83	47
30	tree	9.6	0.0	83	17	60
31	tree	10.4	-0.7	87	13	64
32	tree	13.0	-1.3	100	0	68
33	tree	4.5	-2.7	57	43	77
34	shrub	-2.9	1.5	20	80	51
35	non-woody	-6.2	0.0	4	96	60
36	non-woody	-5.6	-3.9	7	93	84
37	non-woody	-5.1	-4.2	9	91	86
38	non-woody	-5.9	-3.9	5	95	84
39	tree	4.3	-1.1	57	43	67
40	tree	2.9	4.5	49	51	33
41	tree	2.4	7.7	47	53	13
42	non-woody	-2.9	-4.4	20	80	87
43	tree	8.6	-0.4	78	22	62
44	non-woody	-3.8	-3.8	16	84	83
45	tree	4.3	-1.1	57	43	67

46	tree	2.5	3.6	47	53	38
47	tree	-0.6	7.1	32	68	16
48	tree	-1.5	6.0	27	73	23
49	tree	-2.0	6.8	25	75	18
50	tree	-2.0	6.8	25	75	18
51	tree	1.2	7.7	41	59	13
52	tree	11.4	0.2	92	8	59
53	shrub	-3.0	-5.6	20	80	94
54	shrub	-3.9	4.9	15	85	30
55	shrub	-2.8	-2.5	21	79	75
56	shrub	-5.9	0.7	5	95	56
57	shrub	-5.4	0.2	8	92	59
58	non-woody	-4.7	-6.1	11	89	97
59	shrub	-2.3	2.8	23	77	43
60	non-woody	-3.4	-4.9	18	82	90
61	tree	1.9	-2.6	44	56	76
62	non-woody	-4.4	-6.5	12	88	100
63	non-woody	-2.1	-6.0	24	76	97
64	tree	6.0	-1.9	65	35	72
65	non-woody	-4.9	-1.5	10	90	69
66	shrub	1.6	2.5	43	57	45
67	non-woody	-6.3	1.0	3	97	54
68	non-woody	-5.9	9.8	5	95	0
69	shrub	-5.1	2.5	9	91	45
70	tree	5.9	0.1	64	36	59